REMOTE SENSING APPLICATIONS IN FORESTRY

THE USE OF MULTISPECTRAL SENSING TECHNIQUES TO DETECT PONDEROSA PINE TREES UNDER STRESS FROM INSECT OR PATHOGENIC ORGANISMS

By

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Pacific Southwest Forest & Range Experiment Station
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For

NATURAL RESOURCES PROGRAM
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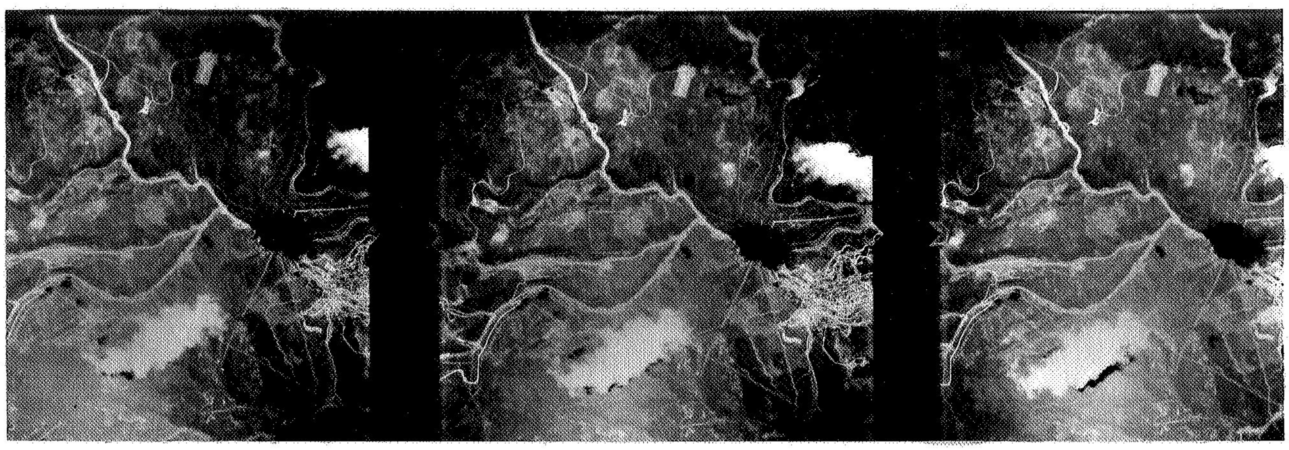

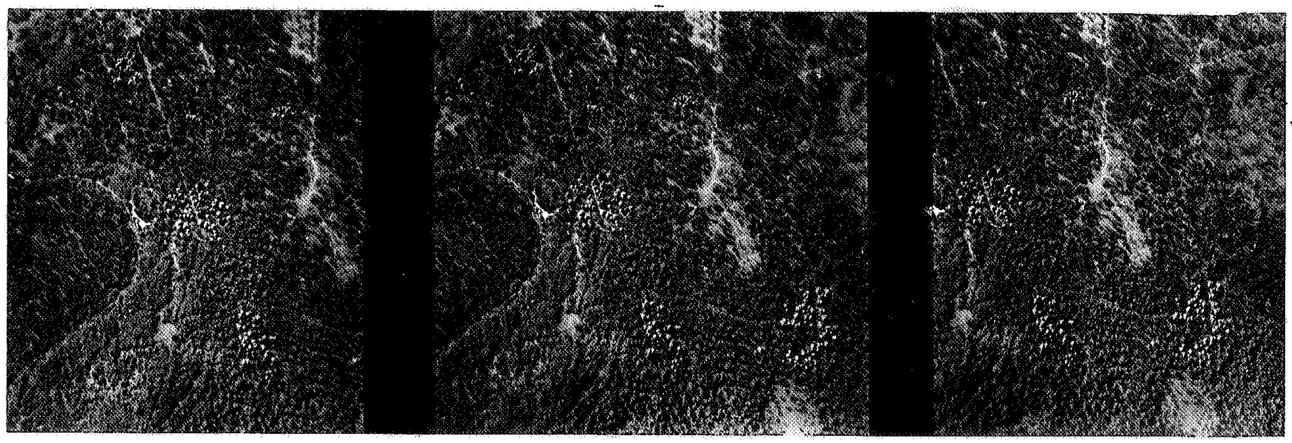

Frontispiece.--Stereo examples of prints made from very small-scale (1:104,000) and normal-scale (1:8,000) transparencies (Kodak Ektachrome Infrared Aero) of Black Hills beetle infestations near Lead, South Dakota. Foliage from ponderosa pine trees attacked one year prior to photography (August 1966) appears yellow to yellow-red; foliage of trees attacked two years ago (1965) appear green on 1:8,000 prints. On the original small-scale transparencies the larger infestation centers are detectable. The coverage of the 1:8,000 scale can be related to the white etched line on the small-scale print.

A B S T R A C T

This is the second report of investigations to detect previsual symptoms of tree mortality by bark beetles in the Black Hills of South Dakota. Both ground and airborne operations were conducted to identify the likeliest sensors available to foresters to detect early tree stress. Aerial photography (color and false color) was taken at five periods (October 1966, May, June, July and August 1967) over six infestation centers to capture the changes in foliage coloration. Optical-mechanical scanning imagery was obtained in three wavelengths (2.0-2.6, 4.5-5.5, and 8.0-14.0 microns) over a three-day period in June 1967.

Better ground instrumentation was developed this season for measuring sap flow, emitted foliage temperature, and meteorological conditions. A promising new device (Scholander bomb) measured highly significant differences in needle moisture tension between healthy and stressed foliage.

Foliage discoloration rates of all 204 infested trees were established by comparison with Munsell cards. Ground Munsell notations of infested foliage were very similar to Munsell notations of the tree images on color aerial transparencies; however, Munsell notations on 35 mm. ground photography showed less agreement with either of the above.

Aluminum and black panels in widths of 2, 4, and 8 feet served as a ground resolution target, 8 by 68 feet, to check thermal and

spatial resolution capabilities of the HRB Singer, Reconofax 11, and the Texas Instruments RS-7 scanner. Temperatures of the contrasting surfaces and the surrounding vegetation were taken with a Barnes PRT-5 radiometer during the thermal flights. Thermal imagery in three wavebands (2.0-2.6, 4.5-5.5, and 8.0-14.0 microns) was much improved over the 1966 trials. The 4.5-5.5 micron wavelengths resolved smaller targets (four feet from 2,000-foot altitude) with better image contrast than the other wavelengths. Tree crowns within a forest canopy could not be distinguished on thermal imagery whether healthy or dying. Individual trees growing in the open and casting strong shadows were distinguishable.

In mid-June, foliage temperatures of dying trees were six to eight degrees C. higher than healthy trees at 1000 hours; the difference was slightly less at 1400 hours (4° to 6°C.). Detectors in optical-mechanical scanners are capable of discriminating temperature differences this small; however, the targets are usually larger in area than dying tree crowns (warm) interspersed and surrounded by healthy trees (cool). Scanners with longer focal lengths and better resolution capabilities are needed before the desired spatial discrimination is attained.

A photo interpretation test showed no difference between two interpreters or two films (color or false color) in their ability to detect dying pine trees. One man located 60 percent of the infested trees in May on both films; this is a significant improvement over the test conducted one year ago. The May aerial photography was taken under a thin overcast which reduced contrast but seems to have enhanced the stressed trees. On the August aerial transparencies, photo interpreters agreed within 95 percent of trees called discolored (faded) by a ground observer; however, they could account for only 80 percent of the total number of infested trees. The remaining 20 percent appeared green on the ground and on the aerial films. A field check will be required in October to determine actual mortality.

Very small-scale (1:105,000) aerial color and false-color films do record the presence of large infestations (20 or more trees) when the foliage becomes yellow red--usually in late August. Small infestation centers are overlooked or appear to blend in with the surrounding vegetation--even at 30-diameter magnifications. More testing of small-scale imagery seems warranted.

A GAF microdensitometer was used to analyse the resolution charts and stressed trees on the thermal imagery. Traces across thermal scan lines obscured the density data. Traces along scan lines permitted quantitative analysis of the resolution target and defined the locations and sizes of tree crowns, forest openings, etc. A beginning was made to relate film density to object temperature.

ACKNOWLEDGEMENTS

This experiment is being performed under the Manned Earth-Orbital Experiment Program in Agriculture/Forestry under the sponsorship and financial assistance of the National Aeronautical and Space Administration, Contract No. R-09-038-002. This is the second report of a cooperative study with the Forest Service, U. S. Department of Agriculture, and involves three Forest and Range Experiment Stations and one Region: the Pacific Southwest at Berkeley, California; the Rocky Mountain at Fort Collins, Colorado; the Intermountain at Ogden, Utah; and the Western Zone Air Unit, Region 4, Boise, Idaho. Salaries of all professional employees are being contributed by the Forest Service.

Special thanks is given to the Homestake Mining Company, Anaconda Copper and Mining Corporation, and the Bureau of Land Management, U. S. Department of Interior for the use of their land and timber to conduct the study.

The Spearfish, Rochford, and Nemo Ranger Districts of the Black Hills National Forest have been particularly helpful in providing darkroom facilities, vehicles, and equipment.

We would also like to acknowledge the excellent ground photography taken by John Schmid at weekly intervals from May through August of study trees. Finally, the efforts by our own forestry technician, Richard Myhre, are recognized for the high quality workmanship in processing all aerial films and for his photographic skills in behalf of this report.

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THE USE OF MULTISPECTRAL SENSING TECHNIQUES TO DETECT PONDEROSA PINE TREES UNDER STRESS FROM INSECT OR PATHOGENIC ORGANISMS

by

Robert C. Heller, W. F. McCambridge, R. C. Aldrich and F. P. Weber

INTRODUCTION

This study is a continuing one aimed at the previsual aerial detection of coniferous trees under stress from bark beetle attack. Our goal is to find which wavelengths or combination of wavelengths in the electromagnetic spectrum (EMS) will differentiate healthy from dying pine trees. After this determination, problems to be solved are to find the optimum altitudes for sensing with various films and filters or with electronic scanners--including side-looking airborne radar.

The first progress report by Heller _et al_, for the period September 30, 1965, to September 30, 1966, summarizes the importance of the problem, previous work done on the ground and in the air, and the work undertaken during the reporting period. During that first year we found that none of the sensors used could detect dying pine trees before the foliage showed visible signs of discoloration--by June and July. Interpretations made then on Anscochrome D/200 film and Kodak Ektachrome Infrared Aero film[1/] detected foliage discoloration indicative of the dying trees equally well. The Texas Instrument Model

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1/ Kodak Ektachrome Infrared Aero film may be designated as camouflage detection (CD) or false-color film in other portions of this report.

RS-7 scanner, operated by the Northern Forest Fire Laboratory of the U. S. Forest Service, produced thermal imagery in three regions of the EMS--2.0-2.6, 4.5-5.5, and 8.0-14.0 microns. But none of this imagery had good enough resolution to discriminate the healthy from dying trees during the two test periods in May and June 1966.

During the first year of the study we also had to learn what ground instrumentation and techniques were needed to evaluate a biological organism as large as a full-grown tree. For example, how does one measure the physiological changes that occur when a mature pine tree is dying? What kinds of instrumentation are needed to measure temperatures inside needles and thermal energy emitted from the foliage? Some of the methods were entirely new; some methods are detailed in the first progress report (pp. 20-28). Many improvements were made during this season and are described in this second report.

Special efforts were made during the past year (1) to obtain thermal imagery with better resolution, (2) to relate insect populations to rates of foliage discoloration, (3) to quantify and compare foliage discoloration determined by one ground observer using Munsell notations with ground color photography and air color photography, and (4) to obtain aerial color and infrared color photography at scales smaller than 1:100,000. Some success was achieved in each of these respects, as reported herein.

LOCATION OF STUDY AREA

The locations of the new attractant sites[2/] in the Black Hills National Forest, South Dakota, are within one-quarter mile of the sites described in the previous report (Fig. 1). The exact location of new infestation sites must change from year to year because we are dealing with two interacting biological organisms: the host tree (ponderosa pine [*Pinus ponderosa* Laws.]), which may die following insect attack, and the attacking beetle (Black Hills beetle [*Dendroctonus ponderosae* Hopk.]), which produces a new brood of beetle and which can fly to other pine trees. Six new attractant sites were established by entomologists from the Rocky Mountain Forest and Range Experiment Station (Fig. 2).

METHODS

During the past season we placed more emphasis on relating aerial imagery to ground conditions. Such information is needed so that we can learn what meteorological, ecological, or physiological interactions will permit us to make previsual detection of tree vigor loss. On the ground we measured the following factors:

1. Beetle populations, their vigor, and size of new broods.
2. Rate of foliage discoloration.
3. Internal, ambient, and emitted foliage temperatures.[3/]
4. Transpiration.

[2/] An attractant site may be defined as an artificially established bark beetle infestation; it is described in more detail in GROUND PROCEDURES.

[3/] Emitted foliage temperatures discussed in this report are apparent temperature readings obtained from radiometers; absolute temperatures can be calculated from apparent temperature X long wave emissivity of the terrestrial object, e.g., aluminum = .05, pine forest = .95, etc.

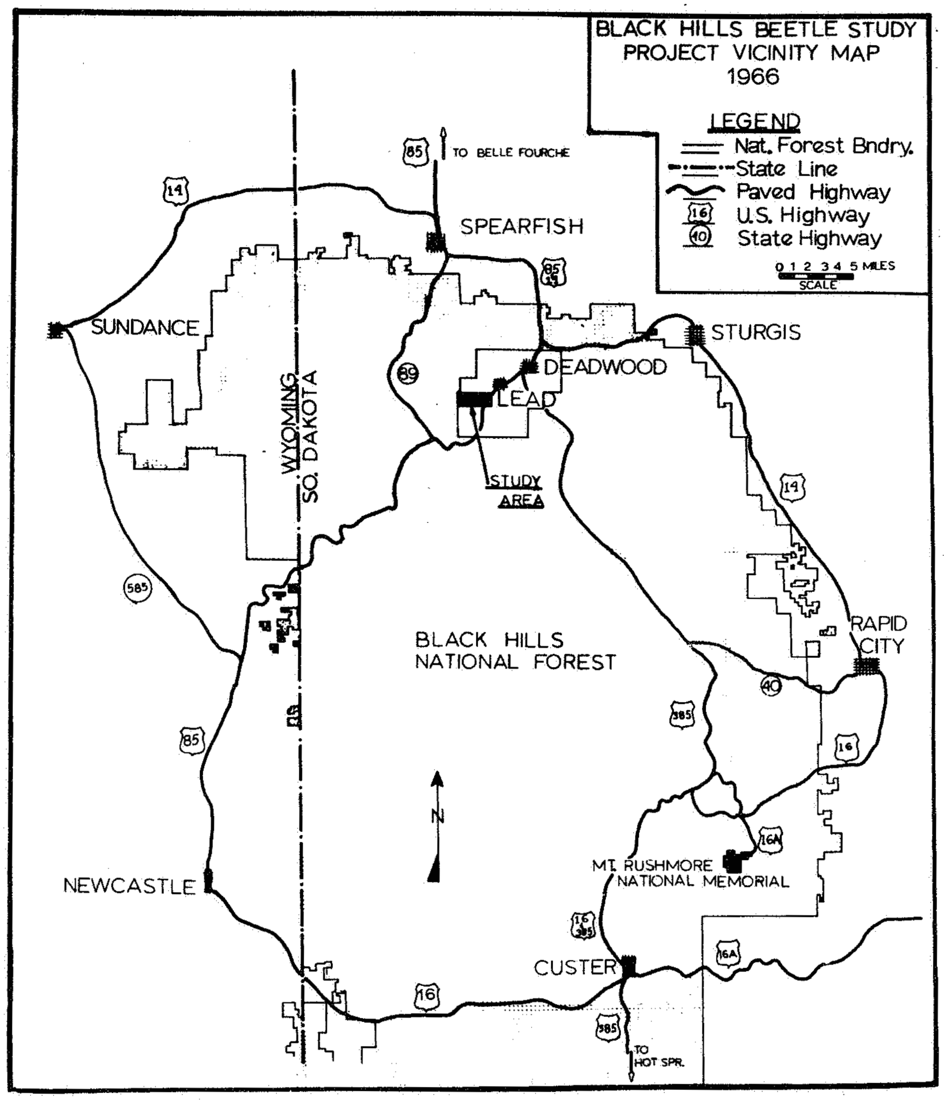


Figure 1.--Location of study area near Lead, South Dakota.

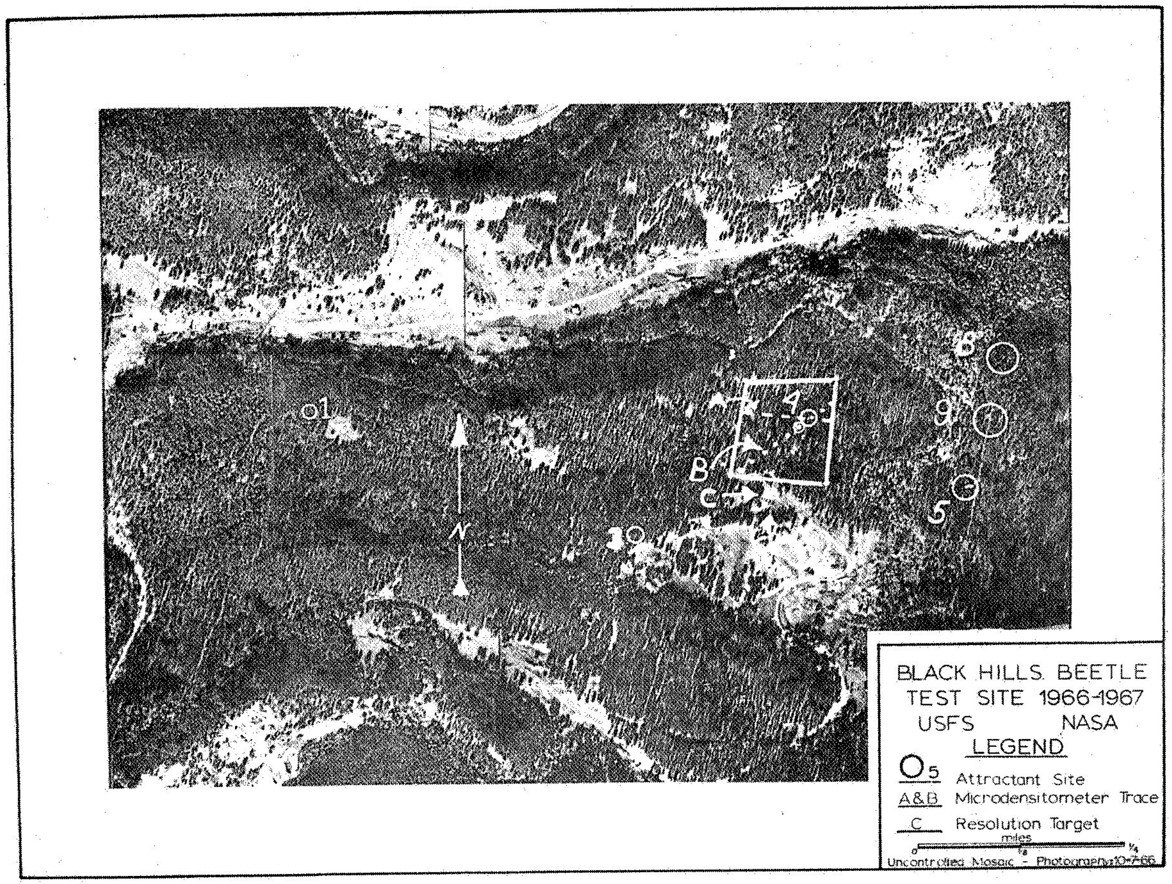


Figure 2.--Location of six attractant sites established near Lead, South Dakota. White circles indicate approximate size and location of each attractant site. Dotted and dashed lines indicate direction of microdensitometer traces across thermal imagery.

5. Solar radiation.
6. Wind direction and velocity.
7. Soil moisture.
8. Moisture tension in needles.
9. Spatial and thermal resolution of thermal imagery.

Most of these data are needed to compute the total energy budget which affects tree growth. For example, the data permit one to explain why trees under moisture stress may produce higher temperatures under similar sunlight conditions than when under no moisture stress earlier in the day. Similarly, one can then hypothesize why thermal imagery may differentiate less vigorous trees from healthy ones in one time period and not in another.

The field schedule and timing coincident with the collection of these data are summarized in Table 1.

GROUND PROCEDURES

Establishment of Attractant Sites

In August 1966, McCambridge again induced bark beetle attack by placing about 300 female beetles in a screen cage stapled to a ponderosa pine at each prospective attractant site. The number of pine trees that were heavily attacked at each attractant site as a result of using the screen cages was as follows:

	Attractant site number	Number of trees attacked
	1	3
	3	4
	4	38
	5	41
	8	40
	9	83
Total	6	209

TABLE 1

TIMING OF GROUND AND AERIAL OPERATIONS -- BLACK HILLS BEETLE STUDY

Date	Ground Operation	Aerial Operation	Imagery Processed	Photo Evaluation	Remarks
1966					
Aug. 15	Female beetles released in screen cages at six attractant sites	--	--	--	Color of healthy pines 5 GY 5/6 - Munsell notation
Oct. 3	210 infested trees located by plane table on the six sites	--	--	--	--
	On attractant site 4, 18 healthy & 18 infested trees selected & physiological studies begun	--	--	--	Implanted 36 study trees with copper constantan wire, began recording emitted foliage temperature, rate of water transport, & meteorological data.
	Constructed 8'x 68' resolution target	12 flight runs over sites with RS-7 scanner in 2.0-2.6, 4.5-5.5, & 8.0-14.0 micron	In-flight processing w/ simultanerous magnetic tape recording	--	Target temps. 40°C different between aluminum & black surfaces

TABLE 1 - (continued)

Date	Ground Operation	Aerial Operation	Imagery Processed	Photo Evaluation	Remarks
Oct. 7	--	Exposed, Plus X Anscochrome D/200, & Ektachrome Infrared 70 mm. film over six sites	Film processed October 8	--	Aerial photography at three scales: 1:1584, 1:130,000 and 1:12,000
Oct. 31	--	--	--	Edited film, interpreted color & CD	No visible foliage discoloration
Nov. 1	Field data transcribed to ADP cards	--	--	Evaluated thermal imagery	Could not resolve resolution target or trees
Nov. 15	--	--	Made photo prints of study area from panchromatic film	--	To be used in field orientation
Dec.	Began hand & microtome sectioning of pine needles	--	--	--	--
1967					
Feb.	Schematic drawings made from plane table surveys of each attractant site	--	--	Evaluated Oct. 7 1:130,000 color & CD	Both films underexposed two stops
March	Data analysis shows up to 7° foliage temp. difference on healthy & infested trees (Table II)	--	--	--	Agrees with findings of Wear (1966)

TABLE 1 - (continued)

Date	Ground Operation	Aerial Operation	Imagery Processed	Photo Evaluation	Remarks
May 1	Began temperature, soil, & transpiration measurements to capture change-over from dormant to active metabolic stages	--	--	--	Sites covered by late snow, 2-3 feet deep
May 7-15	Determined foliage color with Munsell notation. Took samples of 14 trees to establish beetle activity & larval populations. Took weekly color photos of 10 representative trees with 35 mm. camera to record changes	Exposed Anscochrome D/200 & Ektachrome IR color films and black & white IR film	Film processed on site	--	Aerial photographs at 3 scales:1:1584, 1:30,000 and 1:120,000. Exposures good to excellent except for small scale
June 16-17	Set up resolution target for thermal scanners. Measured target & foliage with Barnes PRT-5 & Stoll-Hardy radiometers	87 flights made with HRB Singer Reconofax 11 in Aero Commander	Instantaneous Polaroid prints	Resolution on target about two milliradians on best flights	Negatives processed one week later for imagery printout
		26 flights made with T.I. RS-7 in Convair (T-29)	In flight processing	Resolution on best flights about four milliradians	Tapes sent to Univ. of Michigan for imagery print-out

TABLE 1 - (continued)

Date	Ground Operation	Aerial Operation	Imagery Processed	Photo Evaluation	Remarks
		Exposed Anscochrome D/200 & Ektachrome IR films from twin 70 mm. cameras	Film processed June 18	--	Exposures good except for clouds in small scale photographs
July 17-20	Trees re-examined for discoloration & evidence of mortality	Exposed Anscochrome D/200 & Ektachrome IR color films	Film processed July 19	--	Aerial photography at 2 scales: 1:1584 & 1:176,000. All exposures good
	Completed tree physiology studies	--	--	--	--
	Remeasured insect populations causing tree mortality	--	--	--	--
Aug. 21-23	Made last 35 mm. color exposures of 10 sample trees established in May	Exposed Anscochrome D/200 & Ektachrome IR color films	Processed film August 23	Interpreted all color films at 1:1584 scale	Aerial photography at 2 scales: 1:1584 & 1:8,000. Excellent exposures
Aug. 29-30	Determined Munsell notations of all 210 infested trees	--	--	Used microdensitometer on thermal imagery	--

We found that the variance in numbers of trees attacked at each site was related to the proximity of the new attractant site to large active infestations. There is no reason to believe that one batch of female beetles is more or less attractive than other batches.

Visual Determination of Tree Decline

As was noted in the 1966 report, the success or failure of beetle attack is difficult to assess for many trees until either the trees live or die 9 to 12 months after the attack. Trees which show signs of very heavy beetle attack and exhibit early blue stain fungus growth in the sapwood can be labeled quite confidently as successful attacks. Conversely, trees which pitch out the beetles by copious resin flow can be tagged as nonsuccessful attacks. Unfortunately, there are many trees that show both conditions, and therefore, the prognosis of tree decline and mortality remains in doubt. For example, in October 1966, we determined that almost 20 percent of the ponderosa pine trees (43 of 241) which were heavily infested a year (1965) earlier did not die.

Entomologists have always been aware that some trees survive heavy beetle attack, but until this study they did not realize that so high a proportion of the trees would overcome the twin assault of phloem depletion and blue stain clogging of the water conducting tissues. If we can determine what genetic, physiological, or physical traits the surviving trees exhibit, we may be able to specify to field treating crews which trees to eliminate from insecticidal control operations. One clue is that radiometer readings showed consistently higher temperatures for the infested trees which subsequently died in relation to those trees which did not die.

In October 1966, the locations of all infested trees surrounding the attractant tree were accurately plotted by plane table (Fig. 3). Each tree was numbered with plastic tape for later identification.

The rate of foliage discoloration was followed in two ways: (1) by taking 35 mm. ground color photographs of 10 selected dying trees at weekly intervals from May 1 to August 30, and (2) by having one person who had full color perception take Munsell notations of all 209 infested and 47 healthy trees on four occasions: May, June, July and August. The Munsell hue cards were used quite successfully the previous year (in July) to identify foliage color. By relying on one observer we reduced some of the subjective bias and permitted quantification of the color attributes. Furthermore, we hoped to compare the ground observer's Munsell notations with the 10 trees photographed on the ground and with the same trees photographed from the air.

Intensive Study of Healthy and Infested Trees

Many of the same measurements made the first year of the study were made this past season. Some improvements were made in existing equipment during the past year and some additional equipment and techniques used.

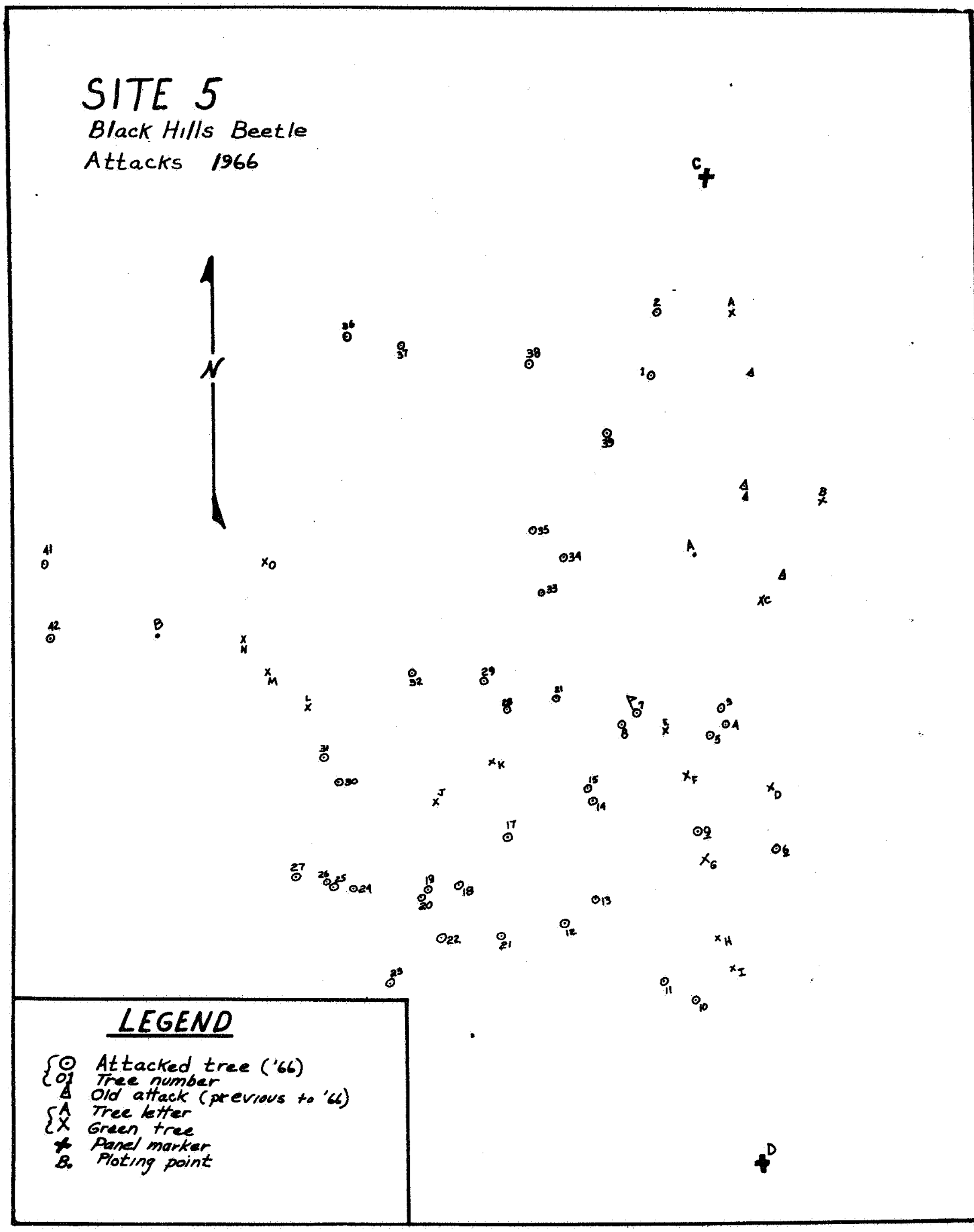


Figure 3.--Plane table map of one infestation site showing panel markers for aerial photography, infested trees, and several noninfested green trees.

To reduce variation among samples, 4 1/2 times as many trees were instrumented this season (36 vs. 8). Half of the 36 trees were healthy and the remaining heavily infested. Measurements again included internal foliage temperature, emitted foliage temperature, and rate of sap transport.

An improved weather station built on a stationary instrument tower (Fig. 4) measured vertical air movement, ambient air temperature, humidity, wind velocity, and solar radiation. Again, soil pits were dug in October, May, June, and July so that soil moisture and temperature probes could be buried in the appropriate soil horizons. The Coleman Soil Moisture Meter was used again to get daily soil moisture and temperature records. Soil samples were obtained for analysis of physical and organic characteristics in the University of Michigan School of Forestry soils laboratory.

Needle moisture tension is one additional parameter measured this season that may help to determine early vigor loss. The technique was first reported by Dixon (1914), and the apparatus improved and described by Scholander (1965). Very briefly the method is as follows: the twig end of a freshly-cut foliage sample (about 4 inches long) is inserted through a rubber "O" ring which is fitted into the top side of a pressurized container (Fig. 5). The proximal end of the twig is exposed to atmospheric pressure. The needle portion of the sample is then placed inside the bottom part of the container and the two parts are screwed together. Nitrogen gas is introduced slowly to the container until free

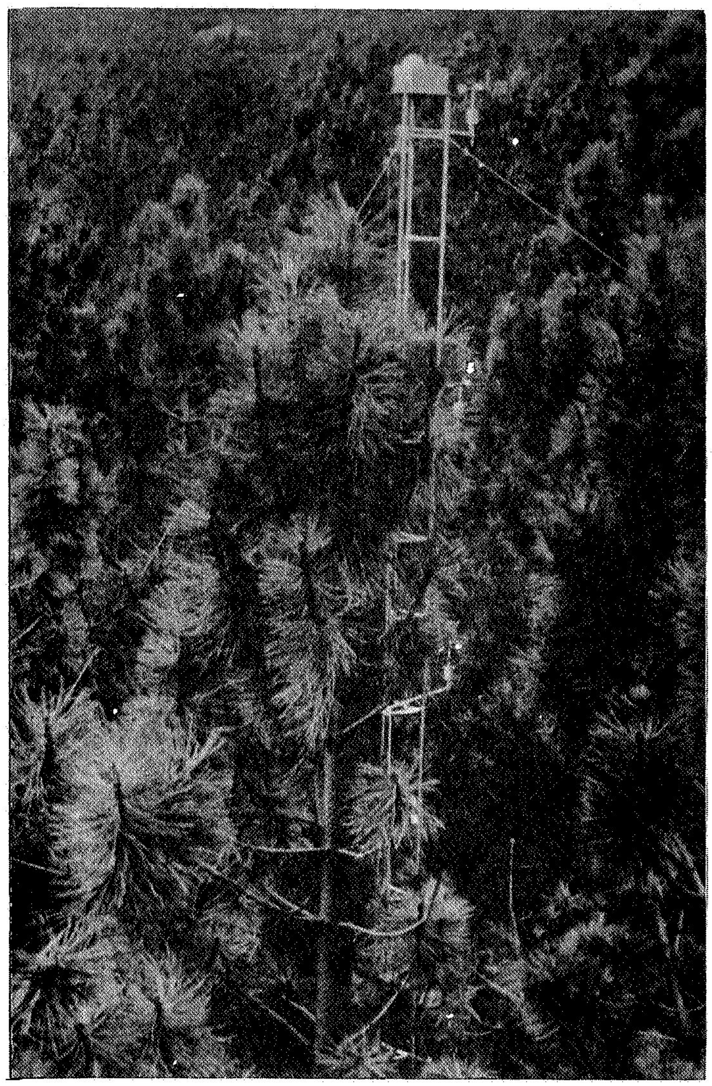


Figure 4.--Stationary 60-foot tower erected to record weather, solar radiation, and to provide a platform for making emitted foliage temperature measurements in the tree tops.

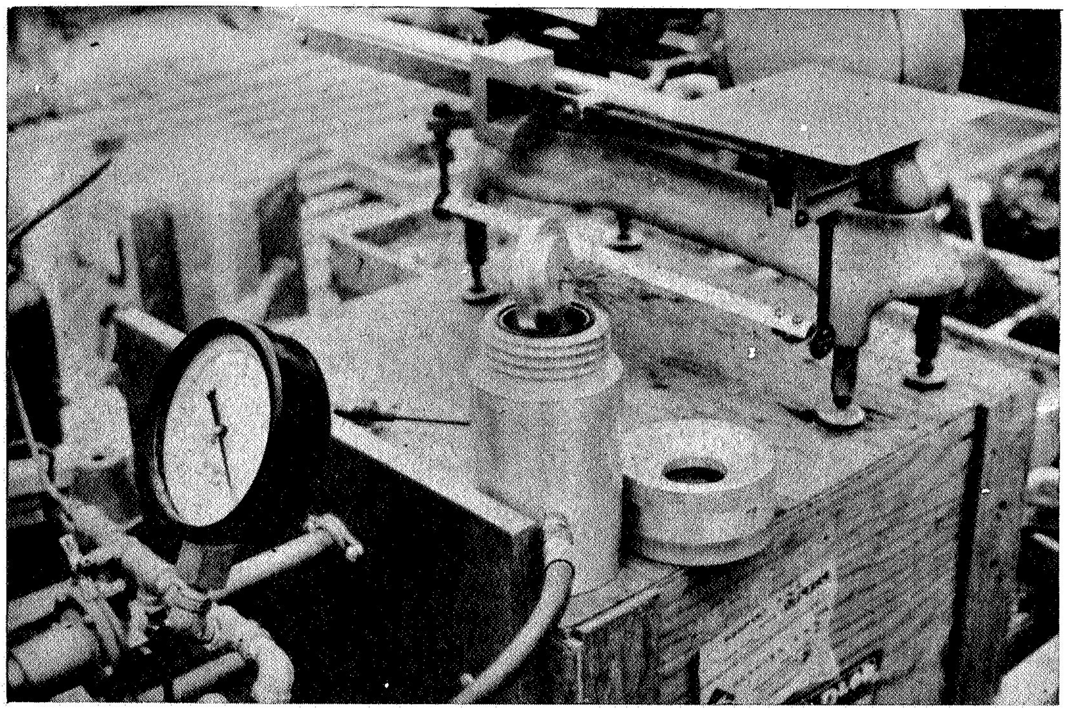


Figure 5.--Scholander bomb for measuring needle moisture tension. Foliage is inserted into top part of bomb, which screws onto cylinder. Pressure gauge reads pounds-per-square-inch required to force water from twig end of foliage extruding from top part of bomb.

water begins to bubble from the tracheid cells in the cut end of the twig (observed with a hand lens). Normal foliage required less pressure to force out the water than foliage from stressed trees. The absolute pressure values--but not comparative values--are affected by time-of-day, season, soil moisture availability, and sunlight conditions.

Moisture stress apparently causes anatomical changes in conifer foliage that influence the reflection of solar radiation from the tree canopy. We tried to study what cellular changes occur in the needles as a tree begins to die. After dehydration and paraffin embedding, longitudinal and cross sections of healthy and stressed (1966 attacked trees) needles were sectioned with a rotary microtome. A series of color slides was made from 15-micron thick sections which were stained with complimentary dyes--safranin to highlight primary tissues and fast green for secondary tissues. Examples of cellular differences are shown in Figure 10 under RESULTS.

<u>Estimation of Beetle Population</u>

Do the development and number of insects under the bark of the infested tree affect the rate of tree foliage discoloration? Two 6- by 6-inch bark samples were collected in both May and July from each of 30 infested trees (15 discolored and 15 green--from the north and south side of each tree) to test the hypothesis that no difference existed in insect activity between trees fading early in the season and late in the season. The 30 trees were chosen at random from 3 of the 6 attractant sites--10 trees at each site. Each 6- by 6-inch bark sample was examined for: the original number of attacking beetles, the length in inches of galleries mined out by them in the cambium layer, and the number of surviving insects.

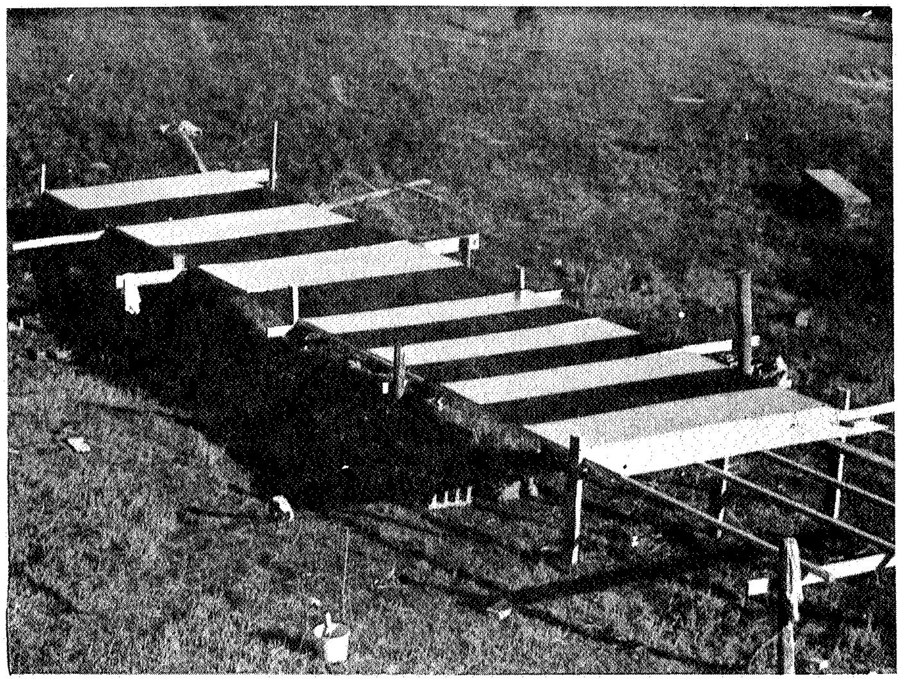
Preparation of Ground Resolution Target

A ground resolution target measuring 8 x 68 feet was constructed in October 1966 to determine spatial and thermal resolution capabilities of the H.R.B. Singer Reconofax 11 and Texas Instruments RS-7 optical-mechanical scanners. Twenty-seven fiberboard panels, each 4 x 8 feet, were covered with 2 mil aluminum foil; the foil was pasted to the smooth side of the panels with wallpaper paste. Half of the panels in widths of 2, 4, and 8 feet were painted with 3M black velvet paint; the remaining panels were left aluminum. They were then laid out in alternating black and aluminum array (Fig. 6).

This target array was designed to test whether the airborne scanners had a 1-, 2-, or 3-milliradian resolution capability. For example, if the 2- by 8-foot panels were distinguishable on the imagery when the aircraft altitude was 2,000 feet above ground, resolution would be 1 milliradian.

The temperatures of the black and aluminum surfaces,[4/] plus the temperatures of the grass and bare soil around the target were recorded with a Barnes PRT-5 radiometer during all thermal flight runs.

[4/] Aluminum surfaces actually reflect the cold daylight sky temperatures.



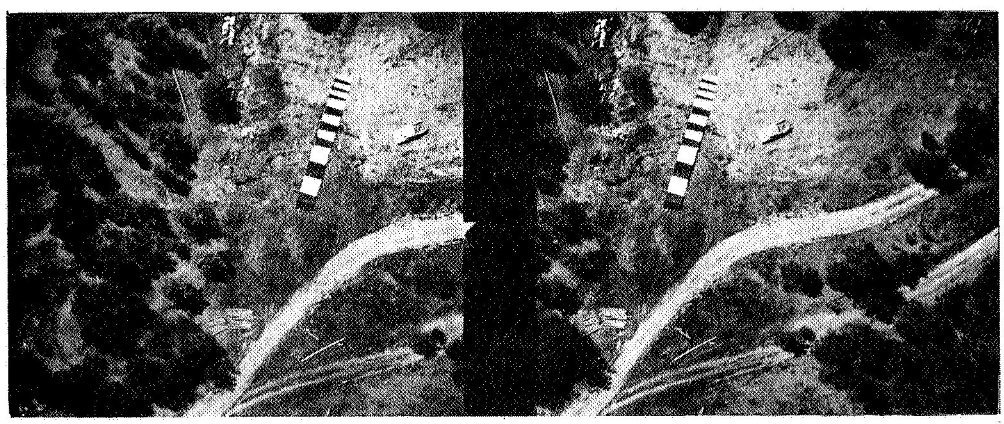


Figure 6.--Resolution target constructed at Black Hills site. Panels were eight feet long and in one of three widths: two feet, four feet and eight feet. They alternated between aluminum painted with black velvet paint and aluminum. Stereo pair shown in lower photograph is from Anscochrome D/200 transparency, scale 1:1,584.

AERIAL PROCEDURES

Aerial Photography

The same twin cameras (Mauer KB-8) were flown from the Pacific Southwest Forest & Range Experiment Station's Aero Commander 500B airplane as described in the first progress report. Three film types were used: Anscochrome D/200, Kodak Ektachrome Infrared Aero, and Kodak Infrared Aero. All six attractant sites were photographed with the color films (natural and false color) in October 1966, and in May, June, July and August 1967 at a scale of 1:1,584. The black and white infrared film was exposed through Wratten A-25 and 89b red filters in May at three scales--1:1,584, 1:30,000 and 1:120,000.

Attempts to simulate near-space photography by using a short focal length lens at medium altitudes--22,000 feet above sea level--were made in October 1966 and in May, June, and July 1967.

All films were processed in a darkroom made available by the Black Hills National Forest in Spearfish, South Dakota. All aerial photography was 70 mm. in size and was processed in Nikor equipment. This procedure permitted us to examine the films within a few hours after exposing them and to make reflights while we were in the area if coverage or exposure was inadequate.

Optical-mechanical Scanning Imagery

Sensing beyond the visible spectrum (0.7 microns) and beyond the capabilities of infrared films (0.9 microns) was done at two time periods and with two different thermal scanners, as follows:

Date	Aircraft Type	Scanner	Number of flight runs by wavelength			
			Unfiltered (0.6-7.0) μ	2.0-2.6 μ	4.5-5.5 μ	8.0-14.0 μ
Oct. 3, 1966	Convair (T-29)	Texas Instr. RS-7	--	4	4	4
June 6, 1967	Aero Comm. 500B	H.R.B. Singer Reconofax 11	7	6	5	--
"	Convair (T-29)	Texas Instr. RS-7	--	4	--	13
June 17, 1967	Aero Comm. 500B	H.R.B. Singer Reconofax 11	11	19	9	--
"	Convair (T-29)	Texas Instr. RS-7	2	2	--	6
June 18, 1967	Aero Comm. 500B	H.R.B. Singer Reconofax 11	2	11	9	--
	Total flight runs (118)		22	46	27	23

The Convair (T-29) airplane, equipment, and research personnel were made available by the Northern Forest Fire Laboratory of the Intermountain Forest and Range Experiment Station. The Aero Commander, scanner, and personnel were detailed to the study area by the Fire Mapping Unit of the Division of Fire Control, Region 4, U.S. Forest Service.

All magnetic tapes made from the RS-7 scanner were forwarded to the University of Michigan for eventual playback by the Infrared Laboratory at the Institute of Science and Technology. At the time of this report, the laboratory has not yet produced any replayed imagery for analysis because of its other commitments.

The Texas Instruments RS-7 scanner does produce imagery on 5-inch wide Hyscan film which is developed in flight. This film was given a final hypo rinse at a darkroom at Ellsworth Air Force Base, Rapid City, South Dakota.

The Reconofax 11 scanner produces 3- by 4-inch Polaroid prints which are immediately available for inspection. It also produces images on 70mm. film, prints of which are shown in Figures 16 and 17.

INTERPRETATION OF AERIAL IMAGERY

Aerial Photography

Interpretations were made of the six attractant sites for all five periods of photography. Beginning with the May 1967 coverage, three kinds of templates were made for each attractant site (Fig. 7). The first template enclosed the boundaries of each site and included

A B C

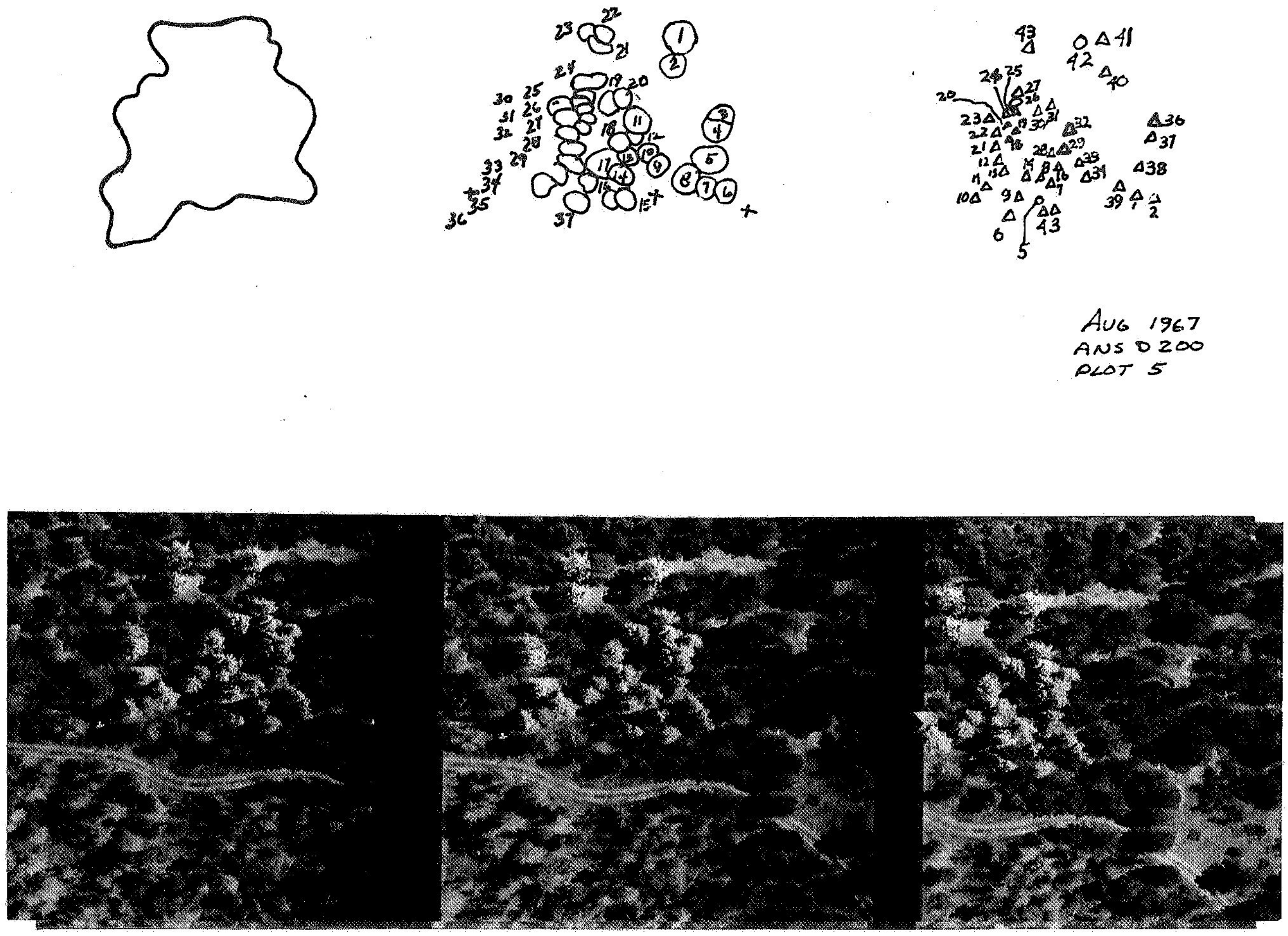


Figure 7.--Photo interpretation templates used on aerial color transparency shown as a color print at bottom. Anscochrome D/200, scale 1:1584.

A - encloses boundary of all infested trees but included many healthy trees

B - circles (O) with numbers indicate trees believed dying by photo interpreter

C - circles (O) and triangles (Δ) are infested trees as determined by ground inspection; numbers correspond with plane table drawing (Fig. 3). Circles represent infested trees which do not appear discolored on ground; triangles represent discolored trees.

as many infested trees as healthy trees. The second was produced by each photo interpreter who circled each tree image which appeared off-color in any way. The third was made from the "ground truth" and is a miniature of the plane table drawing. Infested trees were depicted in two ways on this template; if the trees appeared faded (discolored) on the ground they were shown as triangles (Δ); if not faded at this examination they were shown as circles (○). This third template was used to determine interpreter errors but only after all interpretations were made. Thus, templates were made for each interpreter, film type, flight date, and attractant site--a total of 128.[5]

Optical-mechanical Scanner Imagery

All thermal imagery was reviewed on an illuminated table with a 10-power hand lens to select those examples that best resolved the resolution target. The selection was also based on the ability to resolve tree crowns from the background. Twenty-three flight runs were picked from the Reconofax 11 imagery--no filter (0.7-7.0 micron), 2.0-2.6 micron and 4.5-5.5 micron wavelengths--and four flight runs from the RS-7 imagery in the 8.0-14.0 micron region.

Four identical points which surrounded the ground instrumented site (site 4) and which could be recognized on aerial photographs were marked on this selected imagery (Fig. 8). Several examples of the optical-mechanical scanner imagery can be seen in the RESULTS section of this report (Fig. 16 & 17).

5/ We would like to acknowledge the careful work involved in the constructions of all templates for this test by Steven L. Wert. He also checked the accuracy of the photo interpreter's templates against the master templates.

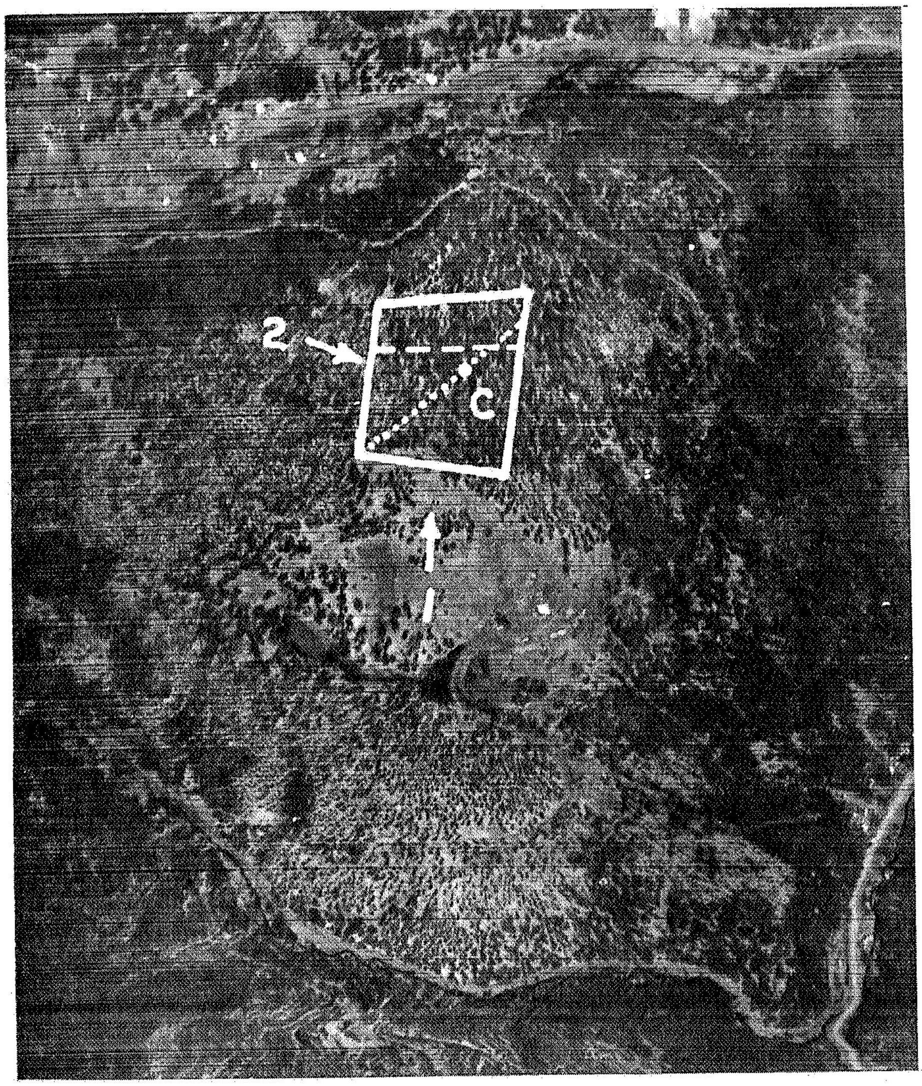


Figure 8.--Optical-mechanical scanner imagery produced by the Reconofax 11 at 4.5 to 5.5 microns over Black Hills site 4. (1) points out 8 by 68 foot resolution chart. (2) indicates four-sided figure which encloses infested dying trees. Dotted line indicates direction of microdensitometer trace across scan line. C indicates center of infestation. Dashed line shows location of microdensitometer trace parallel to scan line. Compare with mosaic made from conventional photography (Fig. 2).

In addition to monocular viewing, examples from all wavelengths of the line-scan imagery were examined with a General Aniline and Film Model 650 microdensitometer (Fig. 9). This was done to quantify which wavelengths were resolved best over the resolution target. Also, we were interested to learn: (1) whether the microdensitometer could separate tree crowns from openings in the forest, and (2) whether subtle differences--not discernible by eye--could be detected among the infested and healthy tree crowns. Thus, on the thermal imagery, warmer crowns should have higher film densities, and indicate dying trees, whereas cooler crowns should represent lower densities on the imagery and might indicate healthier trees.

The extreme versatility of the microdensitometer meant that several tests had to be conducted to learn which combination of aperture and scanning speed would produce the most meaningful data. For example, there are 10 scanning speeds, 4 chart readout speeds, 6 aperture sizes, 5 magnifications, and 4 color filters to choose from. Most of the tests were finally run at the following settings:

Drive scanning rate: 5 mm. per minute

Chart readout speed: 4 inches per minute

Circular aperture: 1.62 mm. in diameter, effective aperture 200 square microns

Magnification: 100 times

Filter: none

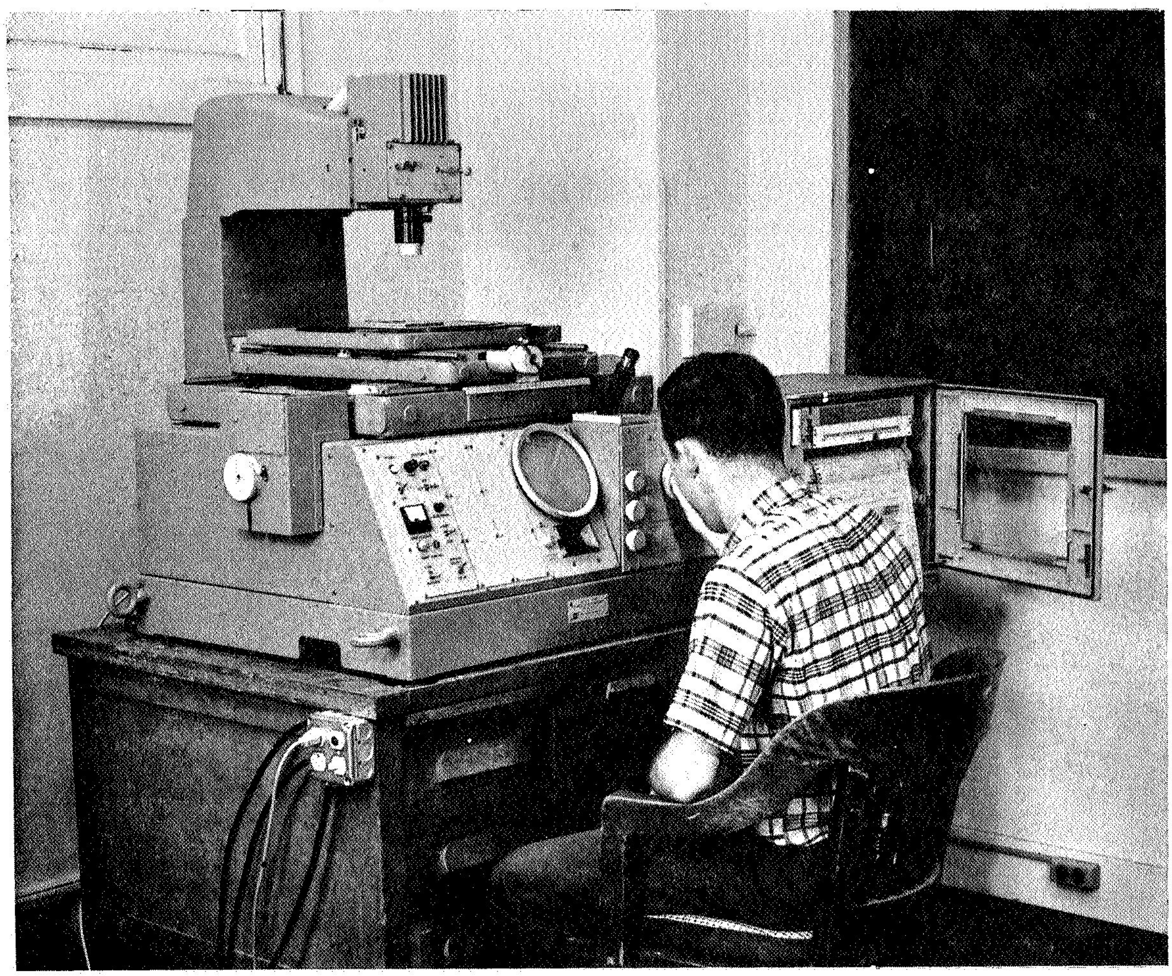


Figure 9.--General Aniline and Film Model 650 Microdensitometer permits microanalysis of black-and-white and color film densities. Density is recorded on chart at right in analogue form from 0 to 4.0 density values.

Representative examples of the microdensitometer charts are shown for both the panchromatic aerial photography and each of the optical-mechanical scanner wavelengths in Figures 16, 17 and 18.

RESULTS

This study is now in its second year. While we still cannot predict the location of low vigor trees by previsual symptoms from airborne imagery, some ground and airborne techniques appear more promising than others. In general, we have learned more about the biological and physical changes which occur in the pine trees as they begin to die. We obtained good records on visual and photographic color changes both on the ground and on aerial transparencies, and were able to get representative very large- and very small-scale color and false-color photography. Optical-mechanical scanner imagery is of better quality than obtained one year earlier. A start has been made on microdensitometer analysis of scanner imagery.

GROUND MEASUREMENTS

Biological and Physical

Effect of beetle population size on rate of foliage discoloration. Based on examination of 60 bark samples, we must accept the null hypothesis that infested pine trees which discolor early have no different beetle populations, length of galleries, or size of the new generation of insects than infested trees which retain their green foliage color. A comparison of the mean values in Table 2 indicates that no difference exists in insect activity between infested, faded, and nonfaded trees.

No consistent difference could be found in these measurements whether they were made on the north or south side of the trees. Inches of gallery length showed the greatest difference--the faded trees having more damage to the inner bark. Student's "T" test, comparing these differences, was not significant.

Visual determination of tree decline. The visual comparisons of foliage color with the prepunched Munsell hue charts are shown in Figure 10. At a glance one can see the shift in hue of the 209 dying trees as the season progressed from May through August. For example, in May about 75 percent of the infested trees were green-yellow, whereas in August the same percentage of trees were yellow-red. The greatest shift from the normally healthy green-yellow (5 GY and 2.5 GY) foliage to off-green foliage (2.5 GY and 10 Y) seems to take place during the fall following attack until the next May.

About 10 to 15 percent of the healthy trees in May, June, and August have a slightly yellow hue (2.5 GY) which is similar to early fading of infested trees. In July, the healthy trees appeared greener; this is probably a result of new needle growth and dropping of old (dead) needles.

When foliage is healthy, it is fairly dark--the average Munsell value (lightness or darkness) being five and the chroma (color strength) 4 to 6. When the tree loses vigor it becomes lighter (the Munsell value goes up to six and seven). The ground observer also noted during May and June that infested trees appeared lighter and more

Table 2.--Numbers of Black Hills beetle adult attacks, live brood, and length of insect galleries in faded and nonfaded ponderosa pine trees per square foot. Based on 60 bark samples from 30 trees (10 trees at each site). July 1967.

	Attractant Site 4		5		9		Average	
	Faded 1/	Non-Faded 2/	Faded	Non-Faded	Faded	Non-Faded	Faded	Non-Faded
1966 Attacks (adults)	8	11	12	10	11	7	10	9
Live broods	25	29	24	18	26	38	25	28
Inches of gallery	136	127	156	148	155	126	149	132

1/ Faded trees averaged 10 Y (yellow) on Munsell notation

2/ Nonfaded trees averaged 2.5 GY (green-yellow) on Munsell notation

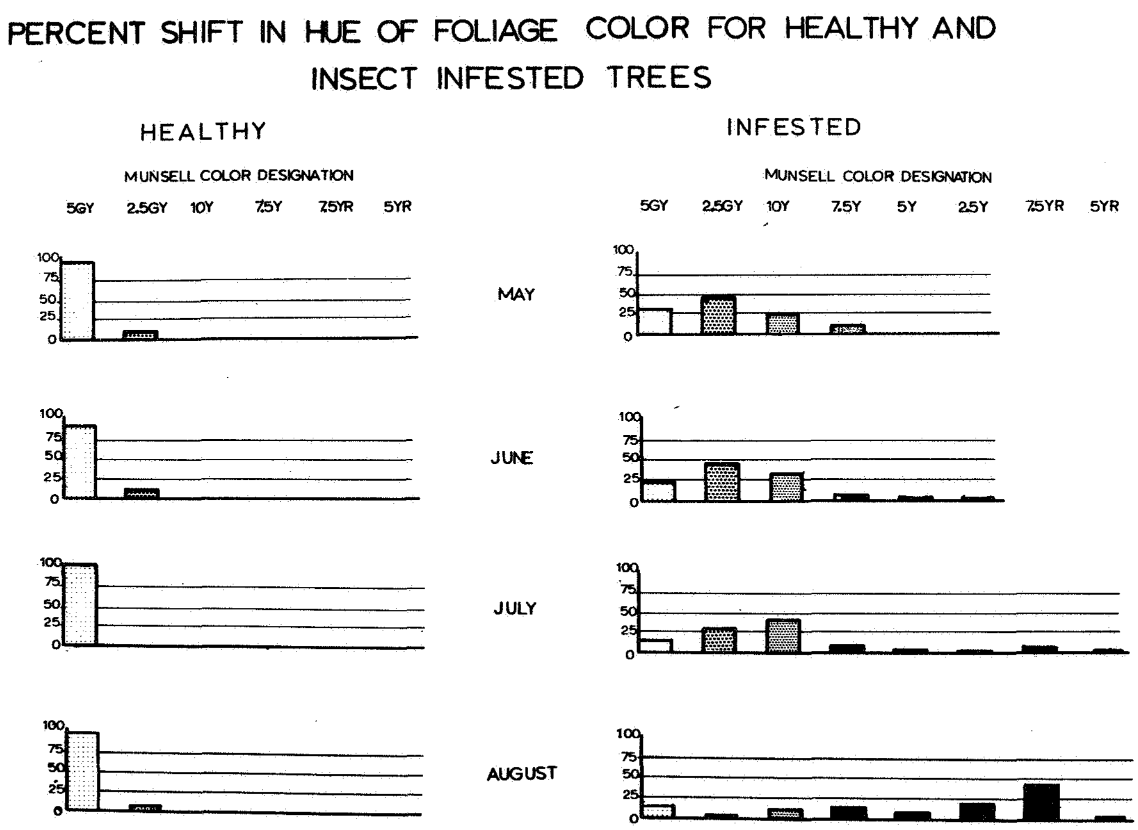


Fig 10.--Munsell notations made in the field of 209 infested and 47 healthy ponderosa pine trees in May, June, July and August 1967.

silvery than healthy trees while both still had the same hue. As infested foliage changes to yellow, the trees become still lighter and the Munsell value becomes 7 to 8 with little change in chroma. The chromas increase appreciably as the foliage becomes drier later in the summer and tends toward the orange or yellow-reds (7.5 YR and 5 YR). It is at this stage in late July, August and September that the infested trees have their highest reflectivity in the visible spectrum. Note that even in August about 12 percent of the infested trees have the same hues as healthy trees. These trees may either not die, and consequently not change color, or may succumb, and discolor in September and October. Only a ground inspection in October will determine the fate of these trees.

Munsell readings made from the ground of 10 sample infested trees are compared with Munsell readings made from ground color photos and with aerial color photos in the discussion of photo interpretation results.

Anatomical changes in needles. In an effort to explain why conifers do not exhibit early symptoms of vigor loss in the reflective portion of the near infrared, we studied examples of needle cross sections taken in October, May, June and July of healthy and infested trees.

In October 1966, two months following insect attack, no real differences at the cellular level could be found between the healthy and infested trees. Differences may be present but the nature of slide material preparation tends to hide small growth differences that might actually be present in the early attack stage.

In May 1967, real anatomical differences showed up (Fig. 11) and are noted in the following comparison:

Structure affected	Normal needle	Needle from infested pine
1. Resin canals	open	collapsed or broken
2. Vascular bundles	most cells filled with cytoplasm	cytoplasm absent
3. Stoma	intact	broken, shrunken, degenerate, closed
4. Cytoplasm	fills out to cell walls	shrunken from cell walls, frequently absent
5. Cell walls	normally thin	thicker by comparison

The various changes that occur within the needles probably affect the reflectance mechanism differently. One would expect that with water loss in the needles infrared reflectance would decrease; however, this seems to be offset by the internal anatomical changes shown above and possible chemical changes associated with water loss. The net effect is no change in infrared reflectance.

Note also that there is no significant breakdown in mesophyll cells of stressed pine needles as there is in stressed hardwood leaves. In the latter case, the mesophyll breakdown theoretically prevents internal scattering of infrared light and reduces reflectance back to the camera. Thus, hardwood images on infrared color film or prints appear darker when under stress than when healthy. With needles under stress, the mesophyll walls appear to remain rigid while the cytoplasm shrinks and withdraws from the cell walls. This could be achieved with a very

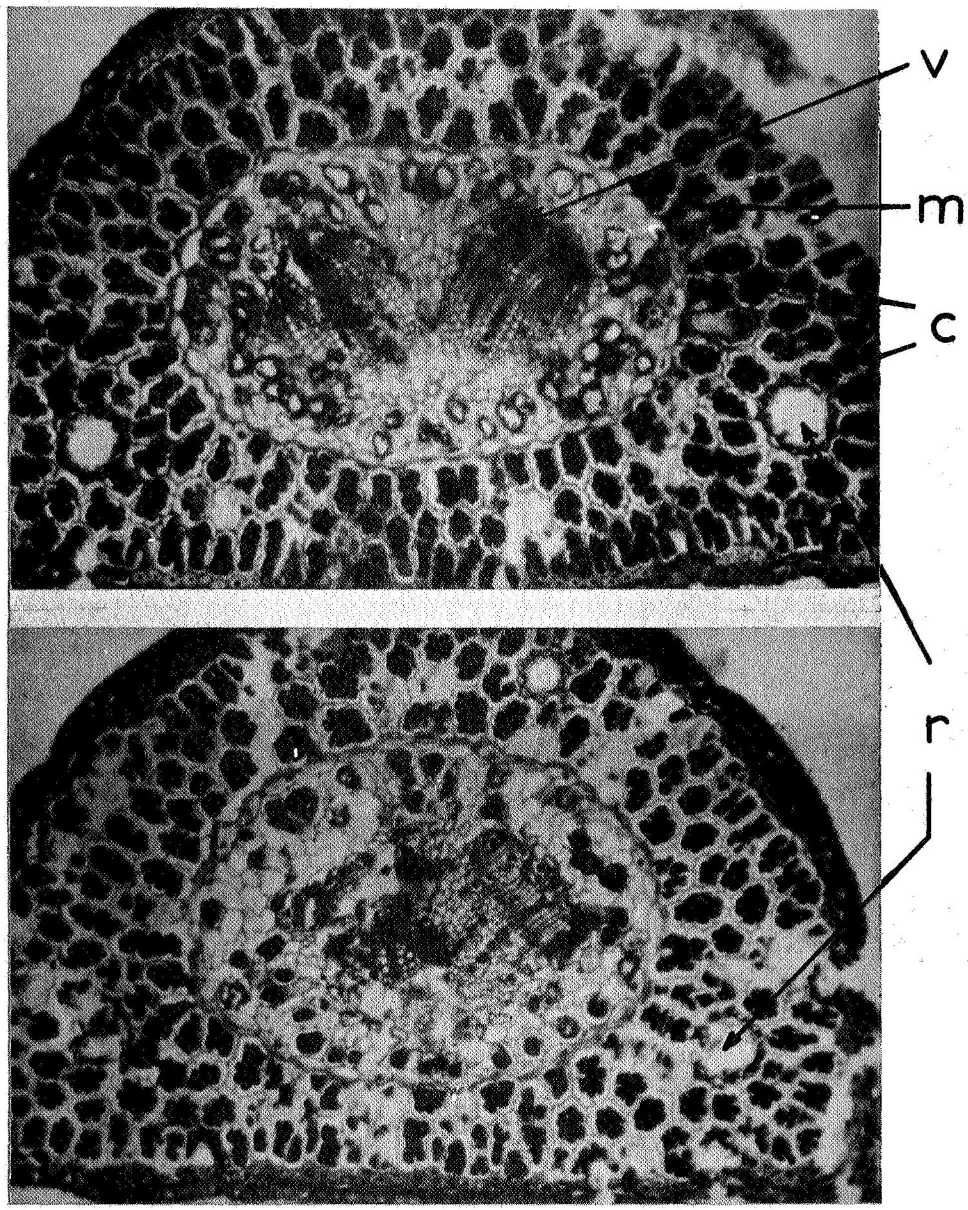


Figure 11.--Cross sections of needle tissue from ponderosa pine. Upper photo is from healthy needle; most cell walls are intact and are filled with cytoplasm. Lower photo is from needle taken from infested tree; many cell walls are broken; vascular bundles, resin canals and stoma are collapsed; cytoplasm is absent or shrunken. r, resin canal; v, vascular bundle; m, mesophyll; c, cytoplasm.

minute transfer of solute. The minute movement of liquid from the cytoplasm results in increasing the concentration of solutes and subcellular particles in the mesophyll; in turn, this decreases the water in mesophyll cells and may contribute to an increased internal scattering or reflectance. Finally, the rigid structure of the pine needle and absence of large parenchyma cells and air spaces in the mesophyll may help explain the difference in reflectance behavior.

Needle moisture tension. This pressure measurement[6] made with the Scholander bomb described earlier may be one of the most sensitive to determine vigor loss in trees. The number of pounds of gas pressure required to force out sap from a freshly cut twig is fairly simple to obtain--even in the woods--and affords a high level of discrimination between stressed and normal trees. Readings made of healthy foliage in the afternoon (1400 hours) were always 2 to 4 times less than those made from infested foliage (Table 3). This suggests making only afternoon measurements when transpiration is probably at a low level.

Table 3 summarizes the climatic and physiological factors that have a bearing on the discrimination of tree vigor. Three typical dates and two time periods (1000 and 1400 hours) were chosen for comparing data between 10 healthy and 10 insect-infested trees.

Foliage emission temperature. These are in situ foliage measurements made with either a Stoll-Hardy or Barnes PRT-5 radiometer from an instrument tower or a neighboring tree. To explain differences in emission temperature, one must consider each sampling period separately

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[6] As mentioned previously in METHODS, the amount of needle moisture tension was measured with a pressure gauge.

Table 3.--Seasonal and diurnal variation of microclimatic and physiological factors which influence discrimination of vigor.

Average of 10 healthy and 10 infested trees

FACTORS	05-07-67		06-16-67		07-14-67	
	Time		Time		Time	
	1000 hrs	1400 hrs	1000 hrs	1400 hrs	1000 hrs	1400 hrs
Solar radiation (Cal/sq cm/sec)	1.10	1.30	1.22	0.95	1.04	1.31
Wind velocity (mph)	3.2	5.8	1.7	4.5	2.6	8.9
Absolute foliage temp. (°C)						
Healthy	14.4	17.2	16.1	19.4	18.3	22.2
Infested	14.7	18.4	20.2	22.6	23.7	24.3
Velocity of sap ascent (cm/hr)						
Healthy	11.0	7.8	8.5	12.9	5.3	5.8
Infested	5.9	5.3	6.1	5.9	1.5	2.1
Leaf moisture tension (psi)						
Healthy	47	45	117	72	78	153
Infested	60	184	259	252	215	280
Foliage emission temp. (°C) (>3.5μ)						
Healthy	16.3	22.8	20.0	19.7	25.3	29.8
Infested	17.9	24.3	24.8	23.5	30.6	32.4

to determine the effect that weather conditions have on the physiological functions of the tree. For example, at 1400 hours on June 16 (Table 3), one might have expected a greater thermal imbalance between healthy and infested trees because of the breakdown in water-conducting tissue in the latter. On this date significant differences do show up in leaf tensions and sap flow; however, while wind velocity was not excessive, incoming solar radiation apparently was. Absence of full sunlight, in this case, was a limiting factor in creating a sufficient differential in long-wave emission. Similar trade-off logic must be used to explain existing thermal differences at any point in time.

The emittance temperatures of the black and aluminum surfaces of the resolution target and the grass on one side of the target are summarized in Table 4. Note that the aluminum targets, which reflect sky temperatures, were 51 to 86 degrees colder than the black targets and 30-50 degrees colder than the surrounding grass.

Table 5 summarizes the emitted temperatures of the infested and healthy trees at the same time periods that thermal imagery was obtained by the airborne scanners. The greatest temperature difference between the infested and healthy trees was recorded at 1000 hours on both days--a 6°C difference on 16 June and an 8°C difference on 17 June. On both days the temperature difference dropped off as the day progressed; transpiration may have been effective in cooling the pine needles in the morning, but dropped off if available soil moisture

Table 4.--Emittance temperatures (in degrees Kelvin) of grass and resolution target measured with a Barnes PRT-5 radiometer - 8.0-14.0μ.

Date	Time	Temperature - Degrees Kelvin			Sky Conditions	Solar Radiation Cal/sq cm/sec
		Resolution Target		Grass		
		Black	Aluminum			
6/16/67	1000	307	233	288	Full sun	1.12
	1200	338	253	294	Full sun	1.35
	1400	320	267	293	Haze	0.95
6/17/67	1000	327	253	293	Full sun	1.14
	1200	339	253	303	Full sun	1.40
	1400	331	260	300	Broken clouds	0.50
	1600	320	269	299	Broken clouds	0.30

Table 5.--Emittance temperatures (in degrees Kelvin) of tree foliage and forest floor in sun and shade as measured with a Stoll-Hardy HL-4 ---spectral bandpass $>$ 3.5 microns.

Date	Time	Foliage in situ 1/ Healthy	Infested	Δ I-H	Forest floor 2/ Shade	Sun
6/16/67	1000	292	298	6	284	303
	1200	292	297	5	293	312
	1400	298	302	4	288	309
6/17/67	1000	291	299	8	285	305
	1200	304	311	7	297	315
	1400	296	301	5	289	312

1/ four samples of each

2/ one sample of each

became critical. A reduced cooling rate and continued full sunlight would cause a rise in emitted temperature. Because of the great volume of weather, physiological, and physical data available (over two growing seasons), a computer program is being written to determine which combination of these variables is limiting, significant, and nonconsequential. It is a job almost impossible to undertake by desk computer, but one within the limits of an electronic data processor.

EVALUATION OF AERIAL IMAGERY

Photo Interpretation

Interpretations from aerial color films still provide the most reliable information on the accurate location and detection of dying coniferous trees. However, we found that May was the earliest any reliable interpretations could be made on color films; still earlier detection of infested trees is needed for control programs to be more effective. Color films exposed over beetle infestations in October, three months after beetle attack did not discriminate infested from healthy trees; these results agree with those discussed in the September 1966 progress report. According to entomologists, dry periods in August and September following beetle attack, occasionally cause early tree discoloration, but these weather conditions have not occurred since this study began.

Bias in interpreting films was minimized (1) by including within the boundaries of each attractant site as many green uninfested trees as attacked trees, and (2) by randomizing the order of photo interpretation of each site, film, and photo date. Thus, each interpreter examined 209 infested trees on each film (2) and photo date (4)--a total of 1672 infested trees plus an equal number of healthy trees. This is about 3400 image determinations that each photo interpreter had to make.

What success did the photo interpreters have in identifying the total number of infested trees at each season? As the percentage of discolored trees increased from 10 in May to 81 in August, as rated by the ground observer, a similar progression showed up on the photo interpretation results. Figure 12 graphically represents the percentage of correct interpretation calls for all variables. The interpreters agreed very well for the three months of June, July and August and also found they did as well in color film as false-color film. These findings substantiate the results from last year. In May, both interpreters were able to find three times as many infested trees on the average as the ground observer. Apparently, the aerial view affords the photo interpreter with more color discrimination than can be detected on the ground. One interpreter picked out more infested trees on the May date than the second interpreter; he did this on all sites and on both films.

A factorial design using season (4), attractant site (4), film type (2), and interpreter (2) as the variables was analysed by analysis of variance. The percent correct interpretations were transformed first to angles where arc $\sin\sqrt{\text{percentage}}$ = angle; this is a procedure developed by C. T. Bliss to permit the mean and variance to be independent for making tests of significance and is described in Snedecor (1950). We found that both the photo interpreters and films did not test significantly different from each other despite the May disparity in correct calls between interpreters. This means that under the test

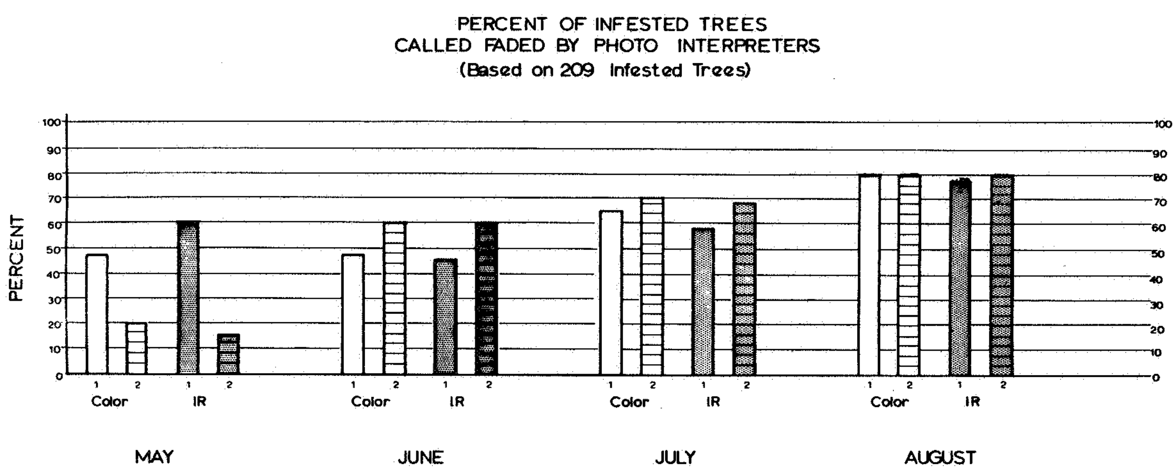

Figure 12.--Comparison of photo interpretation results from two experienced photo interpreters using Anscochrome D/200 and Ektachrome Infrared Aero films at 1:1584 scale with total number of ground-infested trees. Note the increased ability to detect infested trees as the season progresses and also the greater consistency of results obtained by the two interpreters.

conditions, the null hypothesis must be accepted that no interpretation differences could be ascribed to the photo interpreter or film used. However, the differences between attractant sites and season of photography did show highly significant "F" values. True interpretation differences did exist between site and season and served to improve the sensitivity of the factorial design.

How did the photo interpreters compare with the ground observer at each photo period in saying trees were fading? Since the photo interpreters showed sufficiently close agreement in the analysis described above, their results were pooled (Fig. 13). The solid line in this figure indicates perfect correlation (1.0); the plotted points show that, except for May, there is excellent agreement between the interpretations made from aerial transparencies and the ground observations. As mentioned above the photo interpreters picked up about three times as many discolored trees in May as the ground observer.

While the photo interpretations in August only detected 80 percent of the total infested population of 209 trees, the total discolored agrees well with the ground observer. Furthermore, we will not know until October how many more trees will succumb. In 1966, exactly 20 percent of 243 infested trees did not die.

The commission errors, those instances where the interpreters falsely called healthy trees suspected faders, were only one percent of the total number of possible calls (includes healthy and infested trees for all sites). On color film, there were 34 commission errors

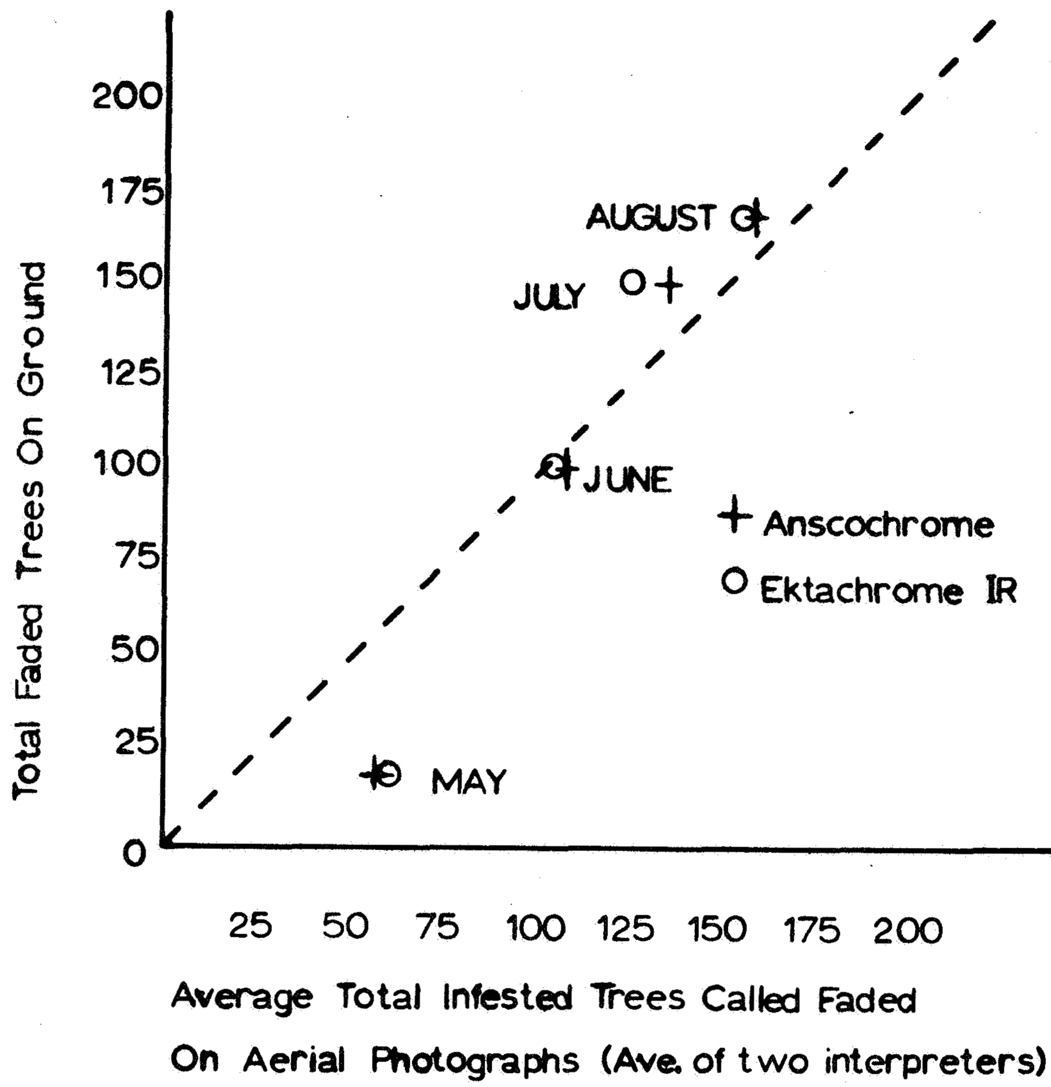

Figure 13.--Comparison of number of discolored infested trees seen on the ground with aerial photo interpretations of same trees. A total of 209 trees were examined by two interpreters on two films--Anscochrome D/200 and Ektachrome Infrared Aero--at each time period. The closer the plotted points to the dashed line--the closer the correlation. Note that photo interpreters discovered more trees in May than the ground observer.

out of a possible 3200 tree images; on false-color film, there were 26 out of 3200. This low rate of error lends confidence in the use of color films for detecting discolored trees.

How do Munsell notations vary by the three methods in which they were used, namely: (1) by ground comparison of the Munsell charts with the 10 sample trees in the field, (2) by comparison of the aerial photo images with Munsell transparencies,[7] and (3) by comparison of the 35 mm. color photos taken of the 10 trees on the ground with Munsell transparencies? The hue comparisons made from the 10 representative trees are shown graphically in Figure 14. There is striking agreement between the ground observations and those made of the identical aerial photo images; they are not over one hue apart at any time period. The changeover from the GY (green-yellow) hues to the Y (yellow) hues occurred in June for the aerial photos and in July on the ground.

While there is a strong correlation in using Munsell color designations to describe dying foliage by the field method and on color aerial transparencies, the correlation becomes weaker when the 35 mm. ground photos are included in the comparison (Fig. 14). All trees appeared two to three hues greener until late July when they were recorded in the yellow hues; they finally approached the yellow-red hues recorded on the ground in August. The rate of foliage discoloration as recorded

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[7] A special viewer, developed and described in a previous study by Heller and Aldrich (1964), permits an interpreter to select Munsell color chips by transmitted light while viewing stereoscopically 70 mm. transparencies, also by transmitted light.

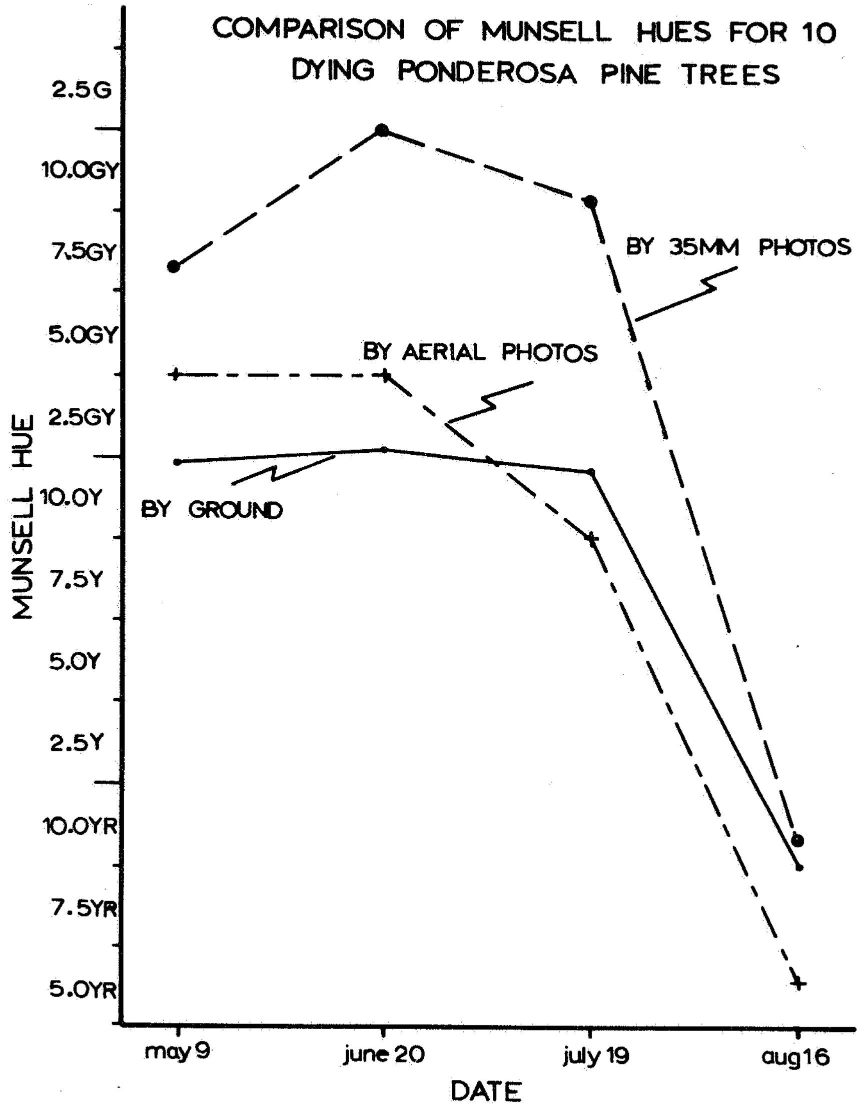

Figure 14.--Comparison of Munsell hues of 10 sample trees taken by three methods at four time periods.

on 35 mm. film during the 12-week period is shown for one of the sample trees (Fig. 15). Note how green the trees appear until late July. We believe that the excessive greenness of the trees is caused by aiming the camera at the tree top which includes blue sky within the foliage. The yellowish foliage and blue sky tend to change the yellows to greens. The background for the aerial photographs included bare ground, dead pine needles, etc., and the background the the visual comparison included only a small circle of foliage seen through the punched hue cards--the skylight was excluded. Thus, we should avoid using ground photography, taken as it was in this study, to record rate of foliage discoloration; the other two methods are more sensitive.

So that the reader may gain an appreciation of the Munsell notation system, a color plate (Fig. 16) has been included to depict the average hues, values, and chromas of the 209 dying trees on August 30. All of these colors were present; the percentage of the number of trees in each hue is shown next to the color chip.

Very small-scale aerial photography. We have much to learn about exposing aerial film at high altitudes to simulate space photography. From previous experience exposing color films at altitudes to 12,000 feet above ground level, reflection-type meters (Weston Master, General Electric, etc.) have provided reliable exposure information. When exposing through a 1.5-inch focal length lens at 22,000 feet above sea level, we consistently underexposed our films by 2 to 2 1/2 times when following the recommended exposure.

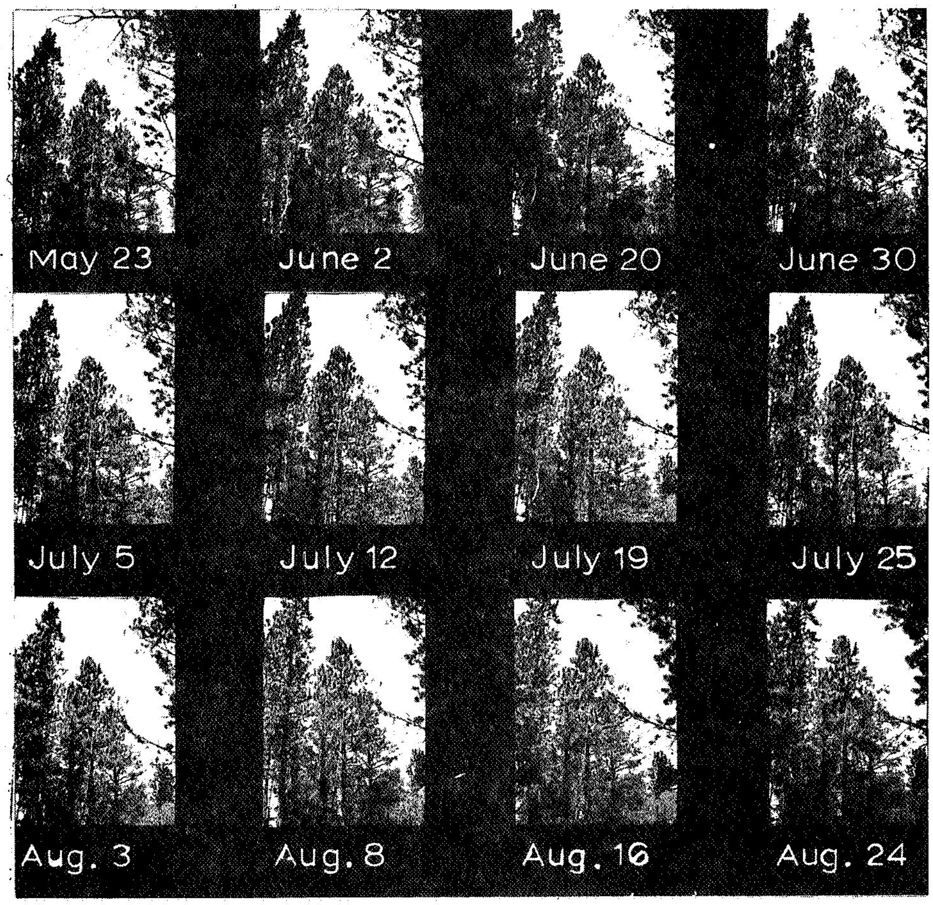

Figure 15.--Reproduction of 35 mm. color slides taken of dying ponderosa pine trees over a 12-week period from May to August.

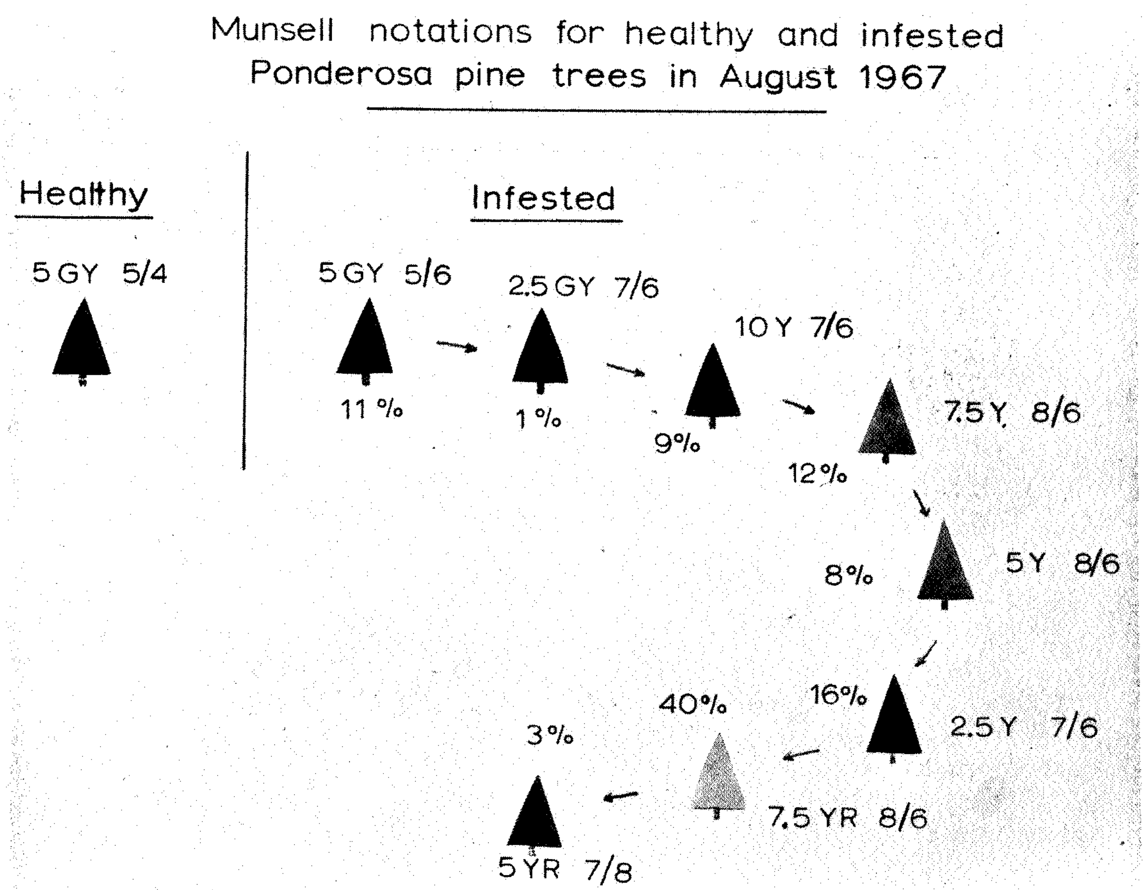

Figure 16.--Munsell color chips representing the color of ponderosa pine foliage on August 30, 1967. The percentage of dying trees represented by each hue is shown to the left of each color chip. The Munsell notation is at the top of each chip. For example, the notation for the chip nearest the bottom--5 YR 7/8--is read as hue 5 yellow-red, value 7, and chroma 8.

In July we obtained our best small-scale aerial photography by deliberately overexposing our films up to three times the recommended exposure meter settings as follows:

	Shutter speed in sec.	f stop
Recommended setting[1/]	1/4,000	4
1 stop overexposed	1/2,000	4
2 stops overexposed	1/1,000	4
3 stops overexposed	1/500	4

[1/] Weston reading-300, film ASA 160.

An example of our best results is shown in stereo in the Frontispiece and was made from the 2-stop overexposure of the Ektachrome Infrared Aero transparency. The scale of this photography is about 1:105,000.

Clouds between the camera and ground reflect unwanted sunlight back to the lens and overexposes ground images around the cloud--in a halo effect. Cloud shadows appear almost black and obscure information in the shadow. Very high-altitude photography will have to be taken under nearly clear skies to avoid the above conditions.

We evaluated the small-scale transparencies with a Bausch & Lomb 70 mm. zoom-stereo microscope. At 15 magnifications, an interpreter can see some of the larger beetle infestation centers and count some of the larger-crowned trees. The larger scale (1:8,000) stereo pair in the Frontispiece is shown below the small-scale transparency to point out where the infestations can be found.

Drainages and hills appear three-dimensional at the small scale but, as Wilson (1967) noted, trees do not have sufficient height to create measurable parallax. Color and shape (or texture) must provide the key for interpreters to detect large infestations. Even at these small scales, both color and false-color films detect the color change when the dying trees reach their peak of color reflectance in the yellow-red hues (August). The technique of using very small-scale color films to follow mortality of large outbreaks--such as the one in Honduras in 1964-65--may be useful for planning purposes. The extensive area coverage available on small-scale photos is a tremendous inducement. Small scales, better lenses, and more experience in exposing the films are indicated for future tests.

Optical-mechanical Scanning Imagery

Visual Interpretation

Both the Reconofax 11 and RS-7 scanners have an effective focal length of approximately 0.9 inches. This was determined by relating distance measured on infrared imagery to distance on 1:3,450 scale panchromatic photos to find the effective scale (Representative Fraction). This scale was then related to flying height to determine the unknown focal length.

$$\frac{\text{Focal length (feet)}}{\text{Height (feet)}} = \text{RF}$$

$$\frac{\text{FL}}{2{,}000'} = \frac{1}{25{,}345}$$

$$\text{FL} = .079 \text{ feet or } .95 \text{ inches}$$

Reconofax 11. This thermal infrared line-scanner resolved the resolution target best in the 4.5-5.5 μ band. Table 6 shows that 60 percent of all flights made in the 4.5-5.5 μ band resulted in ground resolution of better than four feet. Comparable imagery with no filter and with a 2.0-2.6 μ band filter showed four-foot ground resolution of only 22 percent and 17 percent respectively. Good or better target contrast on 63 percent of the 4.5-5.5 μ imagery also indicates the superiority of this bandwidth.

The afternoon time period resulted in better thermal imagery than noon or morning time periods. For instance, 40 percent of the imagery in the afternoon period had better than four-foot ground resolution in all bands. Imagery taken during the morning (0800-1100 hours) and noon (1100-1320 hours) periods resulted in 33 percent and 21 percent respectively. It should be noted, however, that the 2.0-2.6 μ band imagery during the noon period was better than other time periods.

Two statements can be made regarding Reconofax 11 imagery. One, the 4.5-5.5 μ bandwidth resolves four-foot thermal resolution targets better than imagery in the 2.0-2.6 μ band or when no filter is used. Two, in general, afternoon thermal imagery has better resolution and target contrast than morning imagery.

Texas Instruments RS-7. There were only 23 effective flights (Table 7). No flights were made during the period 1100-1300 hours for comparison with Reconofax 11 imagery for that period. When imagery

Table 6.--Ground resolution for the H.R.B. Singer Reconofax 11 at 1500-2000 feet above the terrain during three daylight time periods; June 16-18, 1967.

Time periods	Filtered band width	Total flights	Resolution 8 feet or greater	Resolution 4 feet or less	Target contrast good	Target contrast poor
	(microns)		percent		percent	
0800-1100	no	6	50	50	0	100
1100-1320	filter	10	100	0	0	100
1330-1635		6	67	33	0	100
All periods	------	22	78	22	0	100
0800-1100	2-2.6	21	85	15	15	85
1100-1320	------	13	70	30	15	85
1330-1635	------	7	100	0	15	85
All periods	------	41	83	17	15	85
0800-1100	4.5-5.5	9	33	67	67	33
1100-1320	------	10	70	30	40	60
1330-1635	------	5	0	100	100	0
All periods	------	24	40	60	63	37
------	All bands	87	70	30	25	75

Table 7.--Ground resolution for the Texas Instruments RS-7 at 2000 feet above the terrain during two daylight time periods--June 16-17, 1967.

Time period	Filtered bandwidth	Total flights	Resolution 8' or greater	Resolution 4' or less	Target contrast good	Target contrast poor
	microns		percent		percent	
0800-1100 hours	8.0-14.0	14	85	15	36	64
1300-1500 hours	8.0-14.0	9	67	33	67	33
All periods	8.0-14.0	23	78	22	48	52

from the morning and afternoon periods are compared with Reconofax 11 imagery, we arrive at two general evaluations:
(1) afternoon imagery in the 8.0-14.0μ band is better than morning imagery in terms of thermal target resolution and target contrast, and (2) imagery in the 4.5-5.5μ bandwidth has better target resolution and contrast than the 8.0-14.0μ imagery for the afternoon period.

From the infrared line-scanner flight tests made on June 16-18, 1967, we can make the following evaluation:

Infrared scanner	Filtered bandwidth	Best resolution target contrast 0800-1100	1100-1330	1330-1630	Order of image quality
Reconofax 11	no filter	-----	-----	X	4
	2.0-2.6 μ	-----	X	------	3
	4.5-5.5 μ	-----	-----	X	1
RS-7	8.0-14.0 μ	-----	-----	X	2

These results are not conclusive. As more data are collected under more stringent flight and instrument-controlled conditions, we will re-examine and adjust these results if found necessary.

Microdensitometer Interpretation

The G.A.F. Model 650 Microdensitometer was used to check line-scanner imagery for image densities caused by differences in emitted energy. An example of the best imagery for each of the infrared bands during both morning and afternoon flights was used for the evaluation. Three tests were made:[8] (1) a diagonal trace across the imagery (Fig.17A)

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[8] Only Reconofax 11 imagery; no scan lines were visible on RS-7 imagery.

through a reference point near the edge of attractant site 4, (2) a trace along a single thermal scan (Fig. 17B), and (3) a trace across the image of the thermal resolution target (Fig. 18).

Evaluation of the recorder chart for the diagonal trace (Fig. 17A) is very difficult. Gaps between scans on Reconofax 11 imagery cause regularly-spaced low-density values in the trace. These low-density values tend to mask out thermal differences on the low-density end of the scale. This means that areas of lowest thermal energy (cool) will not show up and the scale of density values is extended beyond the normal range of expected values.

To overcome this, the microdensitometer was set to trace a single thermal line scan passing through attractant site 4. The resultant trace for the 4.5-5.5μ band is shown in figure 17B. Notice that we have reduced the density range to that which has been recorded due to thermal emittance of objects on the ground.

Evaluating densities on the microdensitometer trace is a special art that requires new interpretation techniques. One must determine a scale of density values that represents the various ground objects, i.e., healthy trees, dying trees, stand openings, rock outcrops, exposed soil, grass, and many others. Until further research provides this scale of values, evaluation must be restricted to generalities.

At our present state-of-the-art, three broad interpretations are possible. For example, on the 4.5-5.5μ image (Fig. 17B), (1)

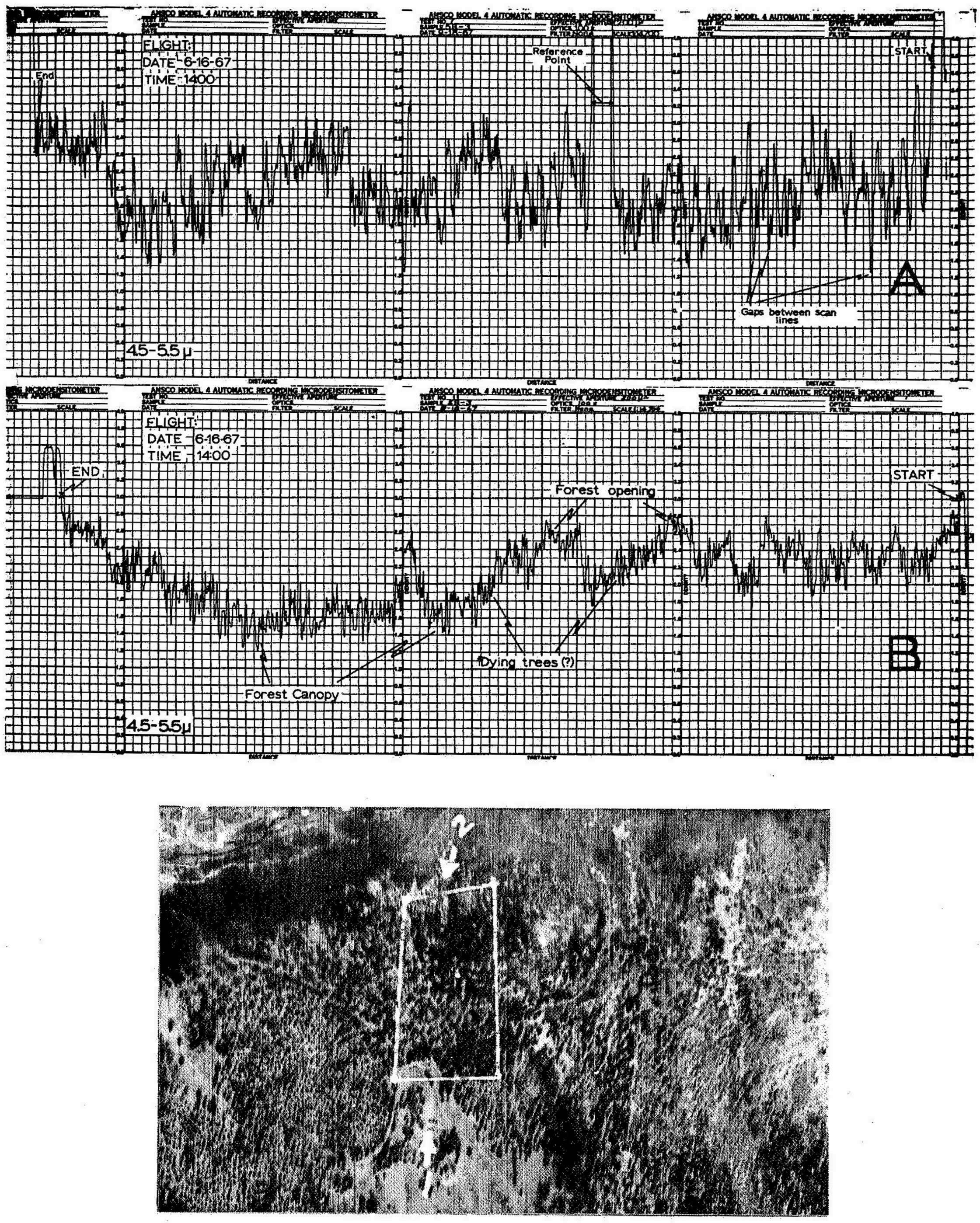


Figure 17.--Microdensitometer traces across Reconofax 11 thermal infrared imagery in the 4.5-5.5 micron band. Flight made at approximately 1400 hours, June 16, 1967. A. Traces diagonally across scan lines. Note regularly-spaced low-density readings caused by gaps between scan lines. B. Trace along scan line. Note the reduced amplitude between the coolest (forest canopy) and warmest (forest opening) objects.

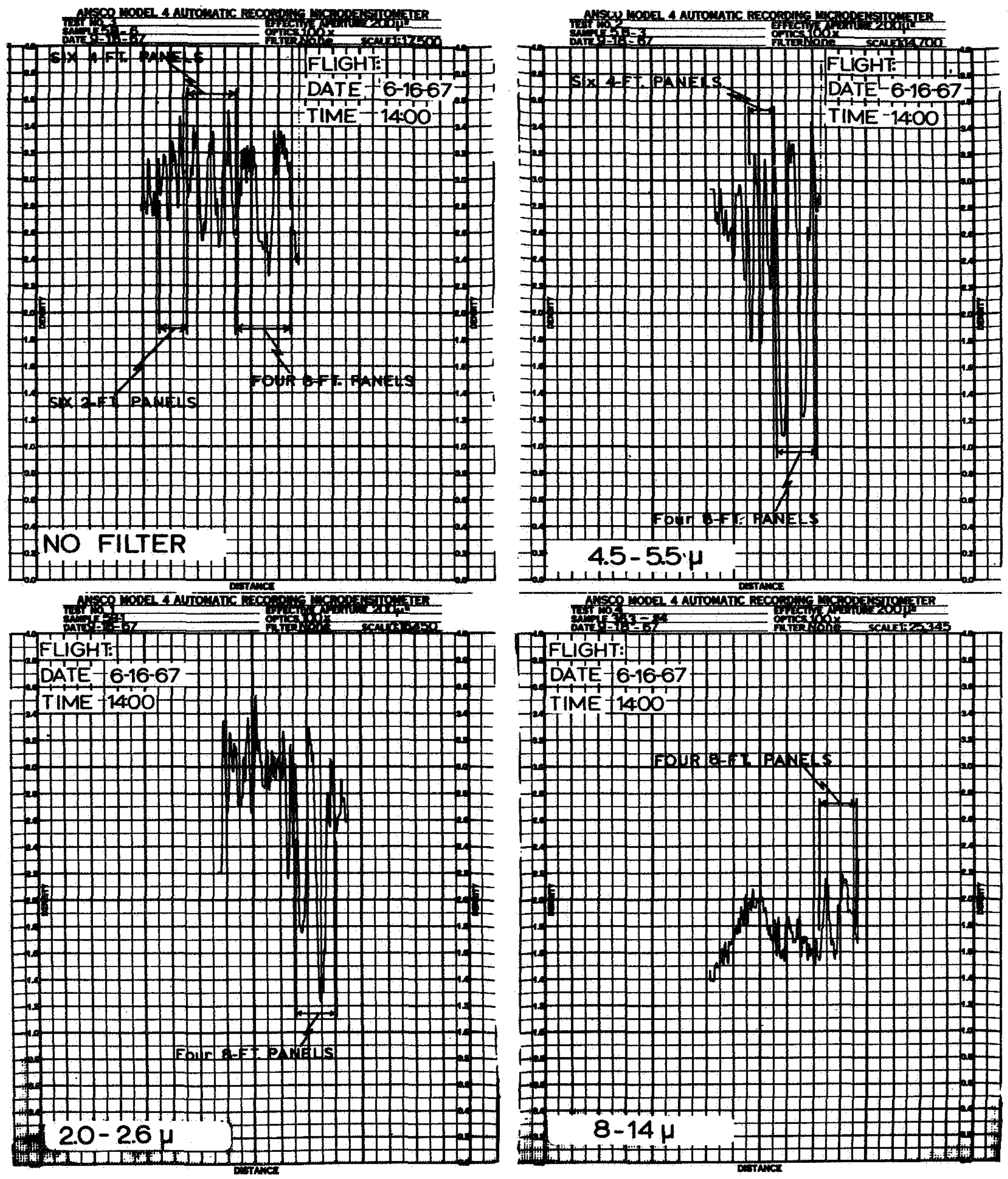
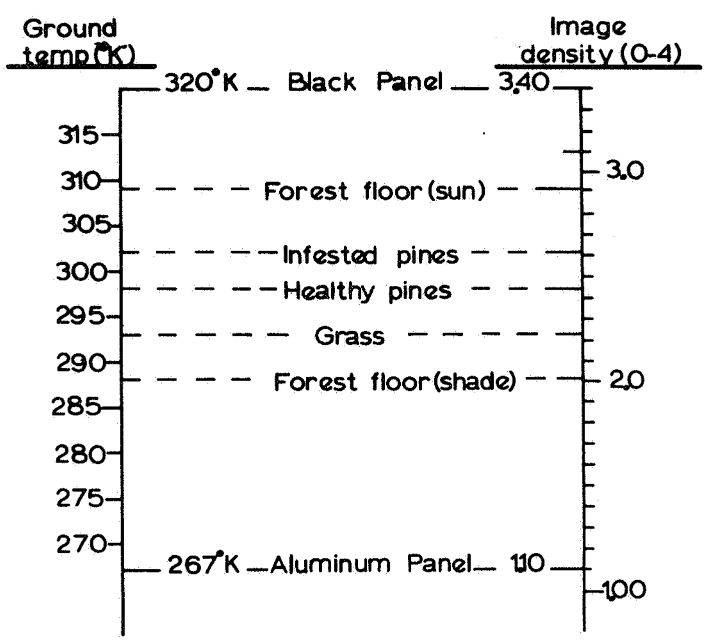


Figure 18.--G.A.F. Microdensitometer traces for thermal resolution targets on thermal infrared imagery taken at approximately 1400 hours, June 16, 1967.

high densities, 2.2-2.8, are openings in the forest stand and warmer than the surrounding forest canopy, (2) low densities, 1.2-2.0, are the forest canopy, and (3) densities between 2.0 and 2.2, which are in the vicinity of dying trees on the ground, may be warmer crowns caused by loss of tree vigor.

Figure 18 shows microdensitometer traces across the thermal resolution target for each of the thermal infrared bands. The highest density (3.5) is recorded for black panels and the lowest density (1.1) for aluminum panels. The temperature difference between panels on the ground, measured with a Barnes PRT-5 Radiometer, was 53°C; the black is much warmer than the aluminum which acts as a mirror and readings made on it reflect temperature of the cold sky. At the same time grass along the side and at the end of the largest black panels was 27°C cooler. The temperatures of various objects in relation to black and aluminum panels are shown in the diagram below.



The density scale in the right of the diagram shows how the resolution target sets the upper and lower limits in thermal emittance by establishing the density limits for interpreting the traces. The example shown was for 4.5-5.5 μ imagery for June 16 at 1400 hours (Fig. 18). Thus, sunny openings in the stand would be expected to register 2.92 on the density scale, infested pines at 2.62, healthy pines at 2.45, grass at 2.24, and shaded openings at 2.01. Unfortunately, these expected values do not coincide with the actual values in figure 17B. Other factors including the gain control on the scanner electronics, scan angle, direction of scan, scattering of emitted energy, and atmospheric conditions will affect the image density.

The microdensitometer trace does set limits of resolution for the infrared scanners. In the illustration (Fig. 18) the best resolution for the Reconofax 11 with no filter was 2 feet. The Reconofax at 2.0-2.6 μ and the RS-7 at 8.0-14.0 μ resolved only 8 feet. Reconofax 11 at the 4.5-5.5 μ band resolves 4-foot panels. Differences in amplitude must be attributed to the direction of the trace and contrast.

How does the resolution for thermal infrared line scanners compare with regular panchromatic photography? Figure 19 shows a microdensitometer trace across the thermal resolution target on Plus-X Aerographic film taken simultaneously with the thermal imagery. Because this is negative material the black panels register as low density and the aluminum panels as high density. The original scale

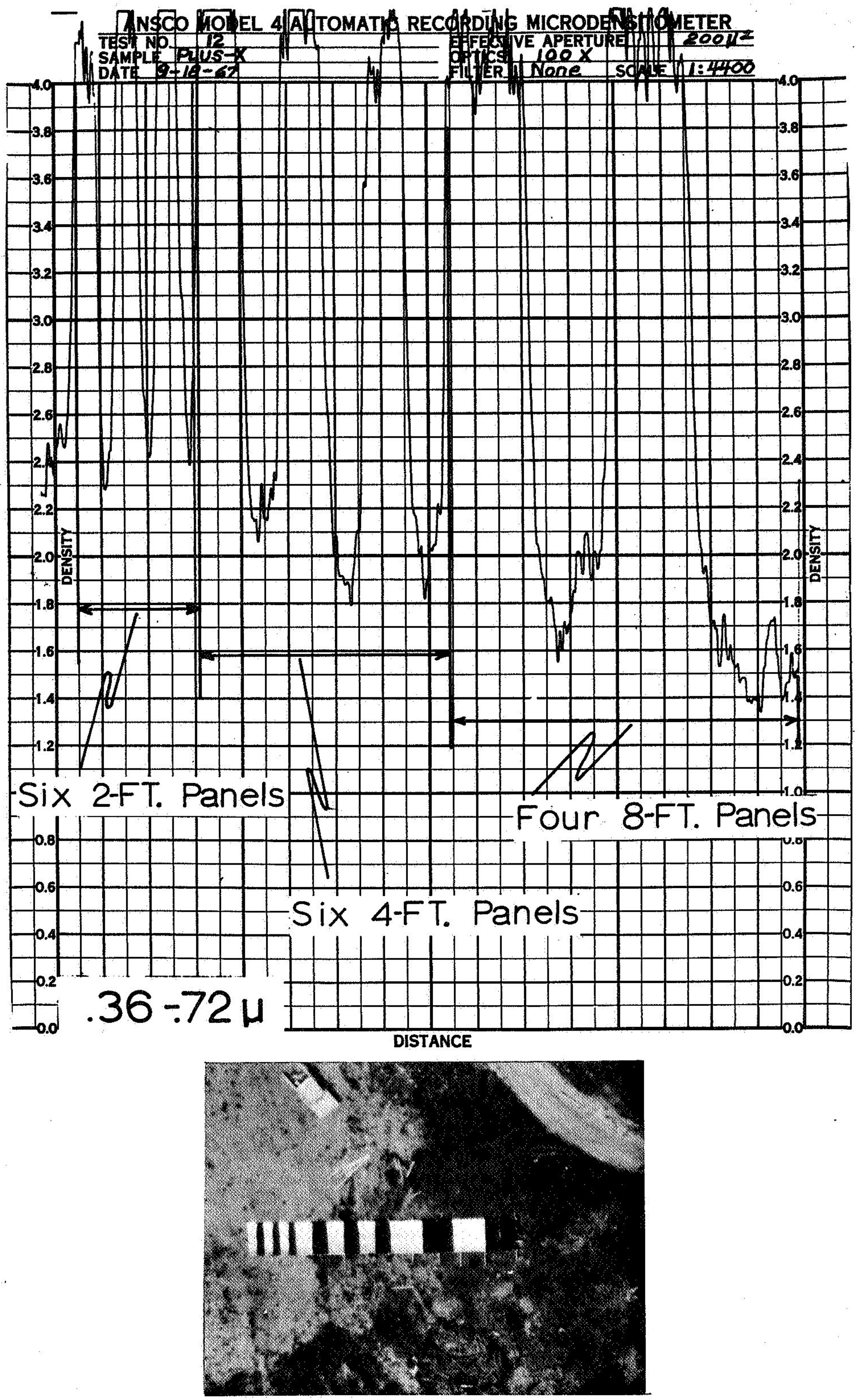


Figure 19.--A microdensitometer trace across the resolution target photographed on Plus-X Aerographic film. The photograph shows the target image at 4X the original 1:4,400 scale.

of the photograph illustrated was 1:4,400. It is obvious that line scanners will need much improvement before they will approach the resolution of ordinary panchromatic photography.

Microdensitometer traces show that subtle differences in thermal emission recorded on film for dying trees are not detectable at the present time. Gaps in the image between scan lines distorts the density scale on traces made across scan lines and makes interpretation impossible. Traces made along scan lines remove this distortion and densities are recorded in their normal range. Warmer openings in the stand and general tree canopy are interpretable from the traces. Traces across the thermal resolution charts help to assess resolution capabilities of the infrared scanners. The high and low density of black and aluminum panels in the chart assign a range in thermal density for the images within the trace. As the resolution panel size decreases, resolution becomes less distinct and the amplitude in density for the change from black to aluminum becomes drastically reduced. This is contrast reduction and though the apparent temperature difference between panels (53°C) is detectable, smaller temperature differences would not be.

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APPENDIX

The following is a list of Forest Service, U. S. Department of Agriculture, personnel who have made contributions to this research study and represent a major salary contribution to it:

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